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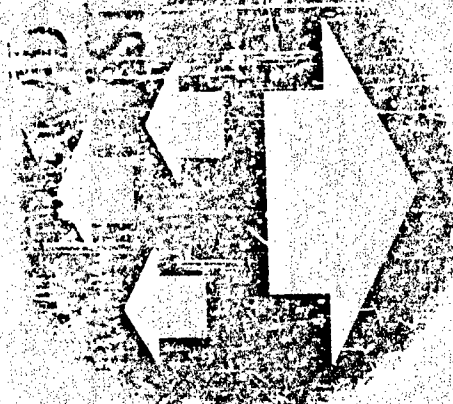
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26 October 1955

Report No. 1030

(Special)

Copy No. 29



VORTEX RINGS IN AIR

Contract Nonr-1498(00)

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26 October 1945

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(Special)

A STUDY OF
VORTEX RINGS IN AIR

Contract Nonr-1498(00)

Written by:

R. Spics

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16 September 1954 to
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This document has been reviewed in accordance with
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Geometry of Aerial Vortex Ring

Pneumatic Vortex-Ring Generator, Diagram

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CONTRACT FULFILLMENT STATEMENT

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I. INTRODUCTION

A. OBJECTIVE

1. A study program with a nominal amount of experimental work is being conducted to investigate vortex rings in air. This work includes, but is not necessarily limited to, theoretical analyses and experimental determinations for the optimum generator design and performance characteristics of a vortex ring in air, for the purpose of focusing energy at a particular point. Incendiary action, pressure-time data, and other pertinent information is being compiled.

2. A thorough literature search has been conducted and a bibliography is included.

B. DEFINITION

1. When a sharp impulse is given to a fluid contained behind an orifice, the flow out of the orifice will tend to curl up at the edge of the plate. This curl will break away and move forward forming a closed loop of vorticity. This is known as a vortex ring. The smoke ring is an everyday example of this phenomenon.

2. The vortex ring is characterized by the fact that the particles of fluid contained in the original ring are transported through the surrounding medium without mass interchange. Furthermore, the large rotational velocities built up around the core result in a low pressure within the ring. Very large quantities of energy are associated with vortex rings.

3. The geometry of the vortex ring is shown in Figure 1. The vortex core of finite size forming the ring is placed around the centerline of vorticity, because some assumption must be made in that region concerning this ring. If an ordinary free vortex were assumed, velocities would become infinite at the centerline. Since this is impossible, Rankine proposed a model where a forced vortex of finite diameter was substituted around the centerline. This is known as the Rankine combined vortex. It is this forced vortex which constitutes the core. Experiments have proved that this model is a correct one, and that a region in which the velocity decreases is found near the vortex-ring centerline.

II. SUMMARY

Work has been conducted for a period of one year on the production and propagation of vortex rings in air. Most of the work has been done with a large vortex-ring generator working on an explosion principle, which produces a ring approximately 3 ft in dia. It has been shown that an upper limit of the energy in the explosion is reached with each generator configuration. After this limit is exceeded, the rings are broken up before they fully form probably by shock reflections from the closed end of the generator. Velocities in excess of 800 ft/sec have been observed during the launching phase.

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II. Summary (cont.)

Pressures within the ring have been observed to be 1.5 psia, or about $\frac{1}{3}$ of an atmosphere. The impact of the ring hitting the ground would indicate that a substantial destructive potential is present, although no quantitative picture can be presented.

III. DESCRIPTION OF THE YEAR'S ACTIVITY

A. Work was started at the beginning of the contract period on a small-scale vortex-ring generator. It consists of a 4-in.-dia cylindrical barrel built up in sections permitting an overall length of up to 4 ft (see Figures 2 and 3). It can be operated either from a compressed air source, or by exploding a 38-gage blank shell. For compressed air operation an air accumulator is attached at one end, which discharges into the generator barrel through a quick-opening valve. This air system may be operated at up to 500 psi, and the amount of air discharged may be controlled by varying the receiver volume by partially filling the vessel with water. For blank-cartridge operation, a firing mechanism is provided on the barrel. Visibility of the rings, once they are generated, is always a problem. With this equipment, copious amounts of dense smoke could be created by burning burlap, and this smoke was used in the formation of the ring. There was also an attempt to use fumes from ammonium hydroxide and hydrochloric acid to give visibility to the ring. Both of these methods, unfortunately, quickly forced the experimenters to abandon any closed place. However, in the open, wind and other extraneous influences made experimentation difficult.

B. Using this equipment with the compressed air source, rings travelling at about 10 ft/sec could be observed. Such rings are to be seen in Figures 4, 5, 6, 7 and 8. Figures 4 and 5 show the ring soon after launching, and the envelope (in the shape of an oblate spheroid) is readily discerned. As the ring progresses, it tends to eject the smoke which, after all, is nothing but minute particles, due to centrifugal force. In Figures 6, 7 and 8, only the core remains. This core is well defined and persists for a considerable time. It is in this region that mass interchange is negligible and large under-pressures may exist. It should be noted that the five figures shown here are not sequential, but are photographs of different rings.

C. When the 38-gage blank cartridges were used, it was found to be much harder to follow the ring with the naked eye. The ring travelled at about 30 ft/sec and did not appear to have as much of the smoke trapped in it. No photographs were taken, but perhaps the higher energy level of these rings (as shown by a greater circulation) ejected the smoke faster. However, it was possible to intercept these rings and feel them strike the body, and to see them deflect objects hung in their path.

D. In order to compile information on the destructive potential of a vortex ring, it was decided to generate a much more energetic ring than was possible with the small, 4-in. generator. For this purpose a piece of equipment originally used in connection with water vortex rings was found suitable.

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III Description of The Apparatus Activity, I (cont.)

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This is a cylindrical tube, 36 in. in dia and 66 in. long. A bell-mouth orifice 16 in. in dia was available for use with this equipment. The aft end of the tube was closed off (Figure 9). After a few exploratory trials with a variety of energy sources, it was decided that the explosion principle of vortex-ring generation would be the most practical. Explosive charges were continually increased in weight to obtain larger energy inputs. Care was taken to introduce the explosion products at the back of the gun in such a way that the flow out of the orifice was kept as smooth as possible. Work was begun using a 10-gauge shotgun shell from which the shot had been removed and replaced with 12.5 g of black powder. The shell also contained an original charge of 8.5 g of gunpowder. This charge produced rings nearly 4 ft in dia travelling at about 100 ft/sec over a range of about 250 ft. It was these rings that first gave the peculiar high-frequency sound (almost a whistle) as they progressed down range, that has become typical of high-energy rings, and can be heard after every launching. The black powder used in these charges was the finest grind available, (FFF-G); some attempts were made to use coarser mixtures, but these did not give satisfactory results. By adding an extension to the shell, it was possible to increase the charge with an additional 14.5 g of black powder, making a total of 8.5 g of gunpowder and 27 g of black powder. This additional energy increased the velocity and range of the ring. The whistle was heard for about 10 sec.

E. Since it seemed probable that enlarging the charge would give better results, a small gas generator was fabricated. This generator took a charge in a metal tube 1.37 in. in dia and 2 in. long, filled with approximately 10 g of black powder. The generator had an orifice .75 in. in dia (.442 sq in.), and produced very satisfactory rings.

F. It was decided that some quantitative results regarding the shape, and velocity of the rings should be collected, and since the rings were too fast for the human eye, high-speed motion pictures were taken. By using a high-speed camera, ring size and shape could be established. The operation of the high-speed cameras makes it possible to print the 120-cycle oscillations of the line current on the film, thus establishing a time scale of the motion being photographed. Velocity measurement was performed by a tube interposed in the ring's line of flight, 5 ft from the mouth of the generator (this tube carried a pressure pickup in some of the tests), and the time it took the ring to reach the 5-ft mark indicated the initial velocity. A typical record is shown in Figure 10.

G. The black powder burning in the gas generator is a solid propellant and its burning characteristics are dependent on nozzle area, density of loading, and area ratios. Every time the charge weight is changed within the same generator, the ratio of nozzle throat area to burning area changes. This parameter is defined as the area ratio and designated by K. Since it is impossible to calculate the actual surface area of each granule of powder, K is redefined as the nozzle throat area per gram of powder. The loading density, designated Δ , is the ratio between free volume in the chamber after the charge is placed, and volume of the charge. Some of this free volume exists between the powder granules, but the density of black powder can be calculated and this real volume found. Closing down the nozzle area for a certain charge will increase the pressure in the gas generator, and since the burning rate

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III Description of the Year's Activity, G (cont.)

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of solid propellant varies with pressure, a higher pressure should give a sharper pressure pulse and, therefore, a faster ring. This is borne out in Figure 11, where the velocities calculated from the films are shown for two nozzle areas, and where the smaller nozzle results in velocities about 10% higher. The exact effect of K and Δ will be discussed later.

H. Films of these first tests showed that a secondary ring was being formed at about the time the first ring was fully formed, as can be seen in Figure 12. It was surmised that this second ring must be a product of a wave returning to the orifice after reflecting off the closed end of the tube, the time interval making this seem plausible. Anticipating the need for pressure surveys through the ring, a pressure pickup with a range from a considerable vacuum up to 100 psi was purchased (Rotishauser type-0A-1, with a 100 psi sensing diaphragm; resolution, one part in 2000, accuracy $\pm 2\%$). This pickup was first used to measure the static pressure inside the ring generator. It was mounted about 5-1/2 in. from the orifice in a radial position. Records obtained were similar to the one in Figure 14, marked $A_w/A_c = .25$. From these

records it was apparent that reflections were the cause of the secondary rings. It was now reasoned that when a shock wave reaches the open end of a tube it is reflected as an expansion wave, while the reflected wave is a shock when the end is closed.

It was logical to assume, therefore, that an exit area existed where the two would cancel out, and no reflected wave would be produced. The assumption was made that this would occur when the orifice opening was one half of the tube area. Upon testing, it was found that a marked improvement resulted, and trying to take discharge coefficients into account, an orifice whose opening was six-tenths of the tube area was then tested giving better results. It was used for the remainder of the year. The contrast is evident in Figure 14. Comparing the photographs of the two rings in Figures 12 and 13, it can be seen that, although the secondary ring is formed with the six-tenths orifice, it is much less energetic and does not travel forward. In Frame 40, this ring is seen to be detached from its tail, while with the original orifice no such separation ever becomes evident. Comparison between the pictures of these two tests shows:

Orifice	$A_w/A_c = .25$	$A_w/A_c = .60$
Charge Weight (g)	38.5	38.5
Nozzle Area (in ²)	.442	.442
Initial Velocity (fps)	312	283
Film Speed (frames per sec)	2255	2320

I. As charge weights were increased, it was found that reflections again became evident and destroyed the ring when large charges were used. By the end of the first year's operation, some calculations based on Rudinger* were made, which explain this phenomenon. The area of the orifice for zero shock reflection is a function of the shockwave Mach number, which means that the contraction ratio changes as the charge is increased (Figures 15 and 16

* see Bibliography

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III Description of The Vortex Activity, I (cont.)

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show this relation). When the first change in orifice was made, charges of 40 to 100 g were used, and these gave peak pressures of from 16 to 30 psia or 25 to 45 psia. As indicated in Figure 16, the correct pressure for a contraction ratio of .5 is 22 psia, and for .6 is 25 psia. Reflections were thus reduced, especially in the low ranges. However, by using the large charges (and higher pressures, about 75 psia = 90 psia), contraction ratios close to 1.00 are needed; work will now be done to verify this.

J. For increasing the energy input to the ring, a new, larger gas generator (No. 2) was built. The gas-generator nozzle area was equal to .422 in.², and charge weights were increased to 90 g. At this point, the limit of the No. 2 generator was reached, and a third one was built. The velocities obtained with this generator (No. 3), as well as those from a much larger one constructed near the end of the program (No. 4), are presented in Figure 17. The curve is shown as continuous in Figure 17, although this result is only inferred, and not proved. The value for K of the two curves overlaps, i.e., K is discontinuous along the curve. The curve levels off at about a charge of 100 g, which indicates that the rings resulting at these energy levels do not form properly. The immediate indication would be a lack of the characteristic whistle. No whistles were heard for either the 100- or the 500 g tests. High-speed photographs reveal that the reflected waves destroy the ring at these high energy levels when this generator configuration is used.

K. The next phase of the work was concerned with the determination of pressure distribution within the ring. For this purpose, a ring generated by a 120-g charge in the No. 3 gas generator was used. Since it was not feasible to traverse a ring once formed, pressures were taken at various points in discrete rings. It was anticipated that underpressures would occur near the core of the ring, and the Kutishauser Type UA-1 pickup was calibrated from -10 to +10 psig, which is possible since the pickup has a connection at the back of the sensor diaphragm. The pickup was mounted on a tube 5 ft from the orifice (Figure 18), and care was taken to place the sensor diaphragm in the meridian plane of the ring. (Figure 1 shows the geometry of the ring.) In this plane, all velocity vectors were parallel to the sensor diaphragm plane, so that only static pressures were registered (see Figure 20). Therefore, the pressure-time relations obtained as the ring passed over a fixed point would be nearly symmetrical. A typical static-pressure record is shown in Figures 20 and 21, these records were taken 14 and 22 in. from the centerline of the ring passed over the pickup. A shock wave precedes the ring in all cases. Since the flow becomes supersonic at certain distances, it was found necessary to place a sharp-edged plate on the pickup, as shown in Figure 22. Calculations could then be made, since the nature of the shock ahead of the sensor diaphragm is determined; (the shock wave from the top of the plate is very weak, since the flow is not deflected).

L. A similar survey of the vortex ring was made to determine stagnation pressures. The pressure pickup was mounted facing the generator. The sensor was again kept in the meridian plane, but this time perpendicular to it. To take care of shock waves during supersonic flow conditions, a hemispheric cap was placed over the sensor (Figure 23). In this case, true stagnation conditions are read only at the intersection of the meridian and

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III Description of The Year's Activity, 2 (cont.)

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equatorial planes. Typical records are shown in Figures 20 and 21.

L. Some relevant information can be obtained from a comparison of Figures 20 and 21. At 14 in. from the centerline, there is a considerable difference between the static and stagnation pressures, although the peak occurs in both at about the same time. This difference indicates considerable velocity at this point. On the other hand, there is virtually no difference between the static and stagnation pressure curves at 22 in. from the centerline, leading to the conclusion that very little velocity is evident here. This is in line with the accented picture of the velocity distribution in a vortex ring, which is indicated in Figure 19; the velocity vanishes to zero at the center of the core.

N. To complete the investigation, the static and stagnation pressures were taken at various distances from the centerline. The pressures at the intersection of the meridian and equatorial planes are shown in Figure 24. From the shapes of the static and stagnation pressure curves alone, a good picture of the ring can be drawn. The minimum point would correspond to the center of the core where the velocity is lowest. The point of inflection in the curve would be the edge of the core, where the velocity suddenly changed, from one due to a forced vortex, to one due to a free vortex. Additional information on the velocity can be gained from the pressures. Computing the pressure ratio (stagnation pressure/static pressure = P_s/P), tables are available for determining the Mach number at this value. If the flow is supersonic, other tables can be used to obtain the pressure ratio across the shock in conjunction with the original table. Using this method, a Mach number distribution (as shown in Figure 14) is found which is relative to the ground, and so the velocity of the ring must be subtracted. An approximate free-stream Mach number based on constant temperature is found to be 4.5. Relative to the ring, then, the velocity is zero at 21.5 in. from the centerline, which corresponds almost exactly with the value found by using the minimum pressure. Furthermore, the maximum Mach number should be at the edge of the core, which is again found to agree closely with the inflection point measurement. From this data, the dimensions of the ring are found:

Core dia	= 5.5 in.
Ring dia	= 43 in.
Ratio	= 7.8

The forward stagnation point is now calculated, on the assumption that fluid is incompressible, and the value is 13.7 in. From the motion pictures, the stagnation point is found to be at 16.3 in. Until a compressible-vortex-ring theory has been more fully developed, this agreement must be considered good.

O. The data presented in Figure 24 represents a substantial contribution for the evaluation of vortex rings; probably the first time that the large underpressures available inside the core of a vortex ring have been measured. These, of course, constitute a large destructive potential. The temperature in the core must be relatively low to account for the low pressure.

C. L. Dailey and F. C. Wood, Computation Curves for Compressible Fluid Problems, New York, John Wiley and Sons, Inc. (1949).

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III. Description of The Year's Activity, C (cont.)

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Assuming the initial process of ring formation to be adiabatic, the temperature in the core must be less than $1/30^\circ$ on the Rankine scale, or about 150° below ambient, although no measurements have been made to verify this.

P. Continuing with the 120 g charges, some work was done to determine the velocity and range of the vortex rings. Much laboratory work has been done and published, giving the decay rates of small rings, of 1 to 5 in. in dia but to the best of our knowledge, no one had ever attempted to determine decay rates for rings of this size. It was not possible to photograph the ring-travel for distances larger than 7 ft making it impossible to use this method to determine time-distance relations. Instead, an observer was stationed in the field at various distances from the generator. The audible signal from the ring (the whistle) was timed as it passed overhead. From this, crude points could be obtained, one for each ring produced, but there is large scatter among these points, as seen in Figure 25. The errors in observation are large near the generator, because the observer's reaction time is large compared with the time recorded, while far from the generator, errors are large, too, since the ring is observed to slow down and advance slowly at that distance. Besides these errors in measurement, extraneous influences such as wind and the proximity of the ground must be accounted for. While every effort was made to choose periods free from wind to perform these tests, air movement was undoubtedly encountered. Furthermore, layers of air of different density can deflect the ring. The results then are hardly conclusive, and only an envelope curve can be drawn. This curve should be tangent to the line marked 500 ft/sec, since that is the measured initial velocity. These results are plotted on log-log coordinates in Figure 26. The fact that the bounding curves seem to have the same slope might indicate that the ring advances at a rate given by the formula

$$S = Kt^{2/3}$$

for a considerable distance. After some time the ring slows down to the point where it virtually hovers in place, and then this exponential curve will no longer hold; nor can it be valid at the very start, since this formula would give infinite velocity at $t = 0$. A parabolic formula is probably needed, but for the purpose of discussion, the exponential form is preferable.

C. An analysis of the initial ring movement, as taken from the high-speed camera film, is shown in Figure 27, where two runs have been plotted and it can be seen that they are similar. A series of straight-line approximations have been drawn through the curve making the analysis easier. After 10 millisecc, when the ring is about 6 ft out, the curve assumes a slope of the order encountered in the envelope curves. The kinks in the curve are not completely understood, but may be due to reflected waves giving short impulses to the ring during its formative phase.

R. A comparison with some of the previously published data can be made. If the exponent of ring propagation is taken to be $2/3$, a velocity distance relation would have to be of the type

$$V = \frac{\text{constant}}{S^{1/2}}$$

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III Description of The Year's Activity, K (cont.)

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A relation similar to this, but with an exponent of $3/2$ for u , is attributed to Tokmachev. Worked backwards, this would mean an exponent of $2/5$ in the ring-propagation equation, which is not observed here. Other experimenters, working over different time ranges, have come up with various exponents. Their results are cross-plotted in Figure 28. All curves have been approximated by equations of the type

$$S = Kt^n$$

The value of K in these relations is of no consequence since it deals mainly with the launching pressure, as can be seen in the curves marked reference 9 in Figure 28 where the lower curve is due to a pressure of 10 psi and the upper one 100 psi. The value of n seems significant, in that it decreases with increasing time. On that basis, the results obtained in this report compare favorably with the curves taken in similar time ranges.

S. As was seen in the last section, the pressure of ring generation does have an influence on the ring velocity, one example of which is that the increase in charge weight results in higher velocities. It was of interest to see how the launching velocity and pressure varied when the charge weight was held constant, but the gas-generator configuration was changed, that is, to investigate the solid-propellant parameters K and Δ . The results are shown in Figures 29 and 30. With K held constant, Δ was varied by means of spacers. The peak pressure was recorded as described herein in paragraph H, and this data is presented in Figure 29. With decreasing K , the curves become flatter and finally assume a negative slope, the important point being that the peak pressure is scattered, with 35 psi being possible on all four curves at different loading densities. When Figure 29 is replotted as it is in Figure 30, with the area ratio as the independent variable, peak pressure is virtually independent of Δ above an area ratio of .008, while below this, there is a divergence of the lines. These results seem to indicate that in the design of the gas generator, the loading density need be only a secondary consideration as long as K is kept above a minimum. Any change in K , however, will effect the peak pressure.

T. A complete summary of all the important runs, from which the quantitative data used in this report were taken, is appended as Table I.

IV. FUTURE WORK

All work now in progress will be carried on with the continuation of Contract NOnr 11498(00). An attempt will be made to produce rings at higher energy levels and to get some data on the destructive potential of these rings; consequently, a full investigation of the wave reflection phenomenon is planned.

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V. BIBLIOGRAPHY

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Ekman, S. K. and Barave, P. V. "On Oberbeck's Vortices," Philosophical Magazine, 3. 7, Vol. 11, No. 73, May 1931.

The authors duplicated Oberbeck's experiments and noticed a sensitivity to their mode of production. Various pressures of generation are investigated, and the results are presented. Time-distance data for various rings are given, and a mathematical theory is developed, but this is proved to be in error by Rutherford and Caldwell.

Bouligand, J., "An Approximate Method of Calculating the Motion of Certain Vortex Pairs," Comptes Rendus (180), pp 2019-2021, June 29, 1925.

An extension of the mathematical analysis of Sadron.

ilder, F. K. and de Bass, H., "Experimental Study of the Formation of a Vortex Ring at the Open End of a Cylindrical Shock Tube," Journal of Applied Physics, Vol. 23, No. 10 pp 1065-1069, October 1952.

The forward velocity of a vortex ring during the first millisecond is investigated. By means of Schlieren spark photographs, curves of axial position vs time are presented. The growth of the ring is also investigated.

Gray, A., "Notes on Hydrodynamics," Part I and II, Philosophical Magazine, 3. 6, Vol. 28, No. 163, July 1914, p 1.

A mathematical treatment discussing the equations of motion and forward velocity of a vortex ring of small cross-section. The author verifies Lord Kelvin's expression

$$V_0 = \frac{K}{\ln a} (\log \frac{8a}{r} - 1/4)$$

Krutzsch, C.-H., "Ueber eine experimentell beobachtete Erscheinung an Wirbelringen bei ihrer translatorischen Bewegung in Wirklichen Flüssigkeiten," Annalen der Physik, 5 Folge, Band 35, 1939.

A paper describing the experiments conducted by the author. He observed vortex rings in water, which, after some distance of travel, developed a scalloping of the core, and later became unstable. The phenomenon is described, and explanations offered.

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V Bibliography (cont.)

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Lauth, A., "Elementare Ableitung der Geschwindigkeit von Kreis- und schrauben wirbeln," Annalen der Physik, IV Folge, Vol. 49, 1916, p 671.

Following the work of Kelvin and Gray, the author is able, without the use of elliptic integrals, to derive the forward velocity of a vortex ring. He finds it to be near "the same as that of Kelvin and Thomson.

Northrup, E. F., "An Experimental Study of Vortex Motions in Liquids," Journal of the Franklin Institute, July - Dec. 1911 (172), pp 345 - 368.

A very extensive series of experiments done on water vortex rings is described. The impact of a ring on a watch chain in the path of the ring is shown, and compared to the fact that the ring will pass through a piece of chiffon without breaking up. Reflections from the surface are described as well as refraction. Entry of a water ring into oil causes an interchange of materials in the ring. This is not true for an oil ring entering water. Experiments with various other materials are discussed.

Oberbeck, A., "Ueber discontinuirliche Flüssigkeitsbewegungen," Annalen der Physik und Chemie, N.F. II, No. 9, 1877.

While investigating the entry of one fluid into another, the author observes vortex rings and describes them.

Reusch, L., "Ueber Ringbildung in Flüssigkeiten," Annalen der Physik und Chemie, Vierte Reihe, 20 Band, 1860.

Both water and aerial rings are discussed. The shape of the generator is investigated, and the conclusion is drawn, that if the length is five times the diameter, no rings will be formed. Orifices of various shapes were investigated, and the conclusion is drawn that rectangular orifices with a 3 to 1 ratio form a doubly-curved lamniscate which pulsates; with a 4 to 1 ratio, two rings appear, and with a 6 to 1 ratio, three rings are produced.

Reynolds, O., "On the Resistance Encountered by Vortex Rings, and the Relation Between the Vortex Ring and the Streamlines of a Disc," Reviewed in Nature, Vol. XIV, No. 477, 1876.

The author investigated vortex rings in water, and came to the conclusion that the rings move without any appreciable resistance. The slowing down is attributed to a growth in the size of the ring due to a continual addition of the surrounding water. Measurements taken show that the momentum at different distances is the same.

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V Bibliography (cont.)

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Rutherford, D. M. and Caldwell, J., "Herbeck's Vortices," Philosophical Magazine, S. 7, No. 61, Dec. 1931.

The authors point out some glaring errors in the analysis of Banerji and Narayana.

Rouse, H. and Hsu, H.-C., "On the Growth and Decay of a Vortex filament," Proceedings of the First U. S. National Congress of Applied Mechanics, 1951, p. 741.

A mathematical treatment which obtains an expression for the change of the vortex characteristics with the passage of time for a line vortex.

Sadron, J., "On the Formation and Propagation of Vortex Rings in Air," Journal de Physique et le Radium, Vol. 7, No. 3, 1926, pp 16-91, Brucher translation 3437.

A study of aerial vortex rings showing the mechanism of formation under experimental conditions. The translational and rotational motion, and the expansion of the vortex, are studied. A parabolic formula for the time-distance curve is given ($t = As^2 + Bs$). The expansion as given is said to be of the form $U = K \log r/r_0$. A mathematical study for the equations of motion and the energy of the ring is given.

Sen, A., "On Circular Vortex Rings of Finite Section in Incompressible Fluids," Bulletin of the Calcutta Mathematical Society, Vol. 13, 1923, p 117.

"On Vortex Rings of Finite Circular Section in Incompressible Fluids," Bulletin of the Calcutta Mathematical Society, Vol. 13, 1923, p 247.

"On Stability of Vortex Rings in Compressible Fluids," Bulletin of the Calcutta Mathematical Society, Vol. 23, No. 1, 1931, p 11.

A series of three papers giving a mathematical analysis of the equations dealing with vortex rings.

Villat, H., "On the Initial Flow of a Liquid Through an Orifice Rapidly Opened," Comptes Rendus (Paris), Vol. 172, 1921, pp 146-150, Brucher translation.

This paper works out the conditions under which, at the start of flow through an orifice, all the delivery comes from the edges of the aperture. Understanding these conditions can help explain the production of vortex rings.

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Dallev, W. L. and Wood, L. C., Computation Curves for Compressible Fluid Problems, New York, John Wiley and Sons, Inc., 1949.

Durand, W. F., Aerodynamic Theory, Volume II, California Institute of Technology, 1943.

Lamp, Sir Horace, Hydrodynamics (Sixth Edition), New York, Dover Publications, 1932.

Milne-Thomson, L. L., Theoretical Hydrodynamics, New York, The Macmillan Co., 1950.

Prandtl, L. and Tietjens, O. G., Fundamentals of Hydro- and Aero-mechanics, New York and London, McGraw-Hill Book Co., Inc., 1934.

Rudinger, G., Wave Diagrams for Nonsteady Flow in Ducts, New York, D. Van Nostrand Co., Inc., 1955.

Tait, P. G., Lectures on some Recent Advances in Physical Science, London, Macmillan and Co., 1876.

Thomson, J. J., A Treatise on the Motion of Vortex Rings, Macmillan and Co., 1883.

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TABLE I
AERIAL VORTEX RINGS
SUMMARY OF MAJOR RUNS

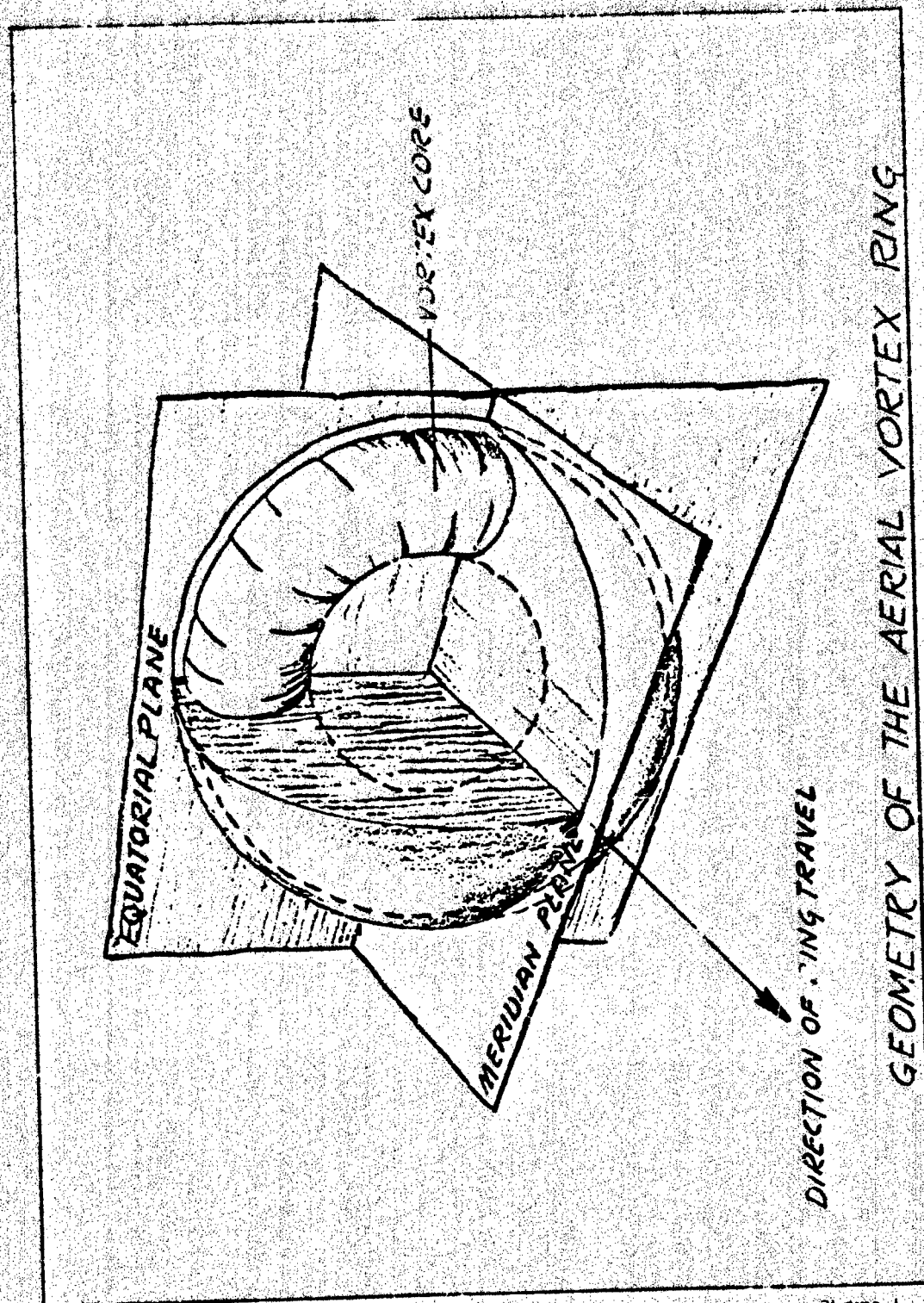
Movie Frame Number	Charge Weight lb	Gas Generator Number	Nozzle Area in ²	Orifice Number	K in ² /gm	Free Vol Powder Vol	Launching Velocity feet/sec
						1.27	218
8003	21.5	1	.442	1	.0180	1.22	312
8060	38.5	1	.442	1	.0115	1.21	330
8061	41.0	1	.442	1	.0108	1.27	244
8064	24.5	1	.196	1	.0080	1.82	395
8122	80	2	.442	1	.0055	1.82	397
8123	80	2	.442	1	.0055	1.82	344
8125	38.5	1	.196	1	.0051	1.22	283
8146	38.5	1	.442	2	.0115	4.65	246
8147	40	2	.442	2	.0111	2.76	307
8148	60	2	.442	2	.0074	2.22	338
8149	70	2	.442	2	.0053	1.82	361
8150	80	2	.442	2	.0055	1.51	364
8151	90	2	.442	2	.0049	8.22	278
8700	40	3	.785	2	.0196	5.15	380
8699	60	3	.785	2	.0131	4.28	419
8701	70	3	.785	2	.0112	3.61	435
8704	80	3	.785	2	.0098	3.10	461
8702	90	3	.785	2	.0087	2.70	461
8703	100	3	.785	2	.0079	2.08	538
8512	120	3	.785	2	.0065	2.08	500
8513	120	3	.785	2	.0065	7.04	652
9590	200	4	3.14	2	.0157	7.04	652
9591	200	4	3.14	2	.0157	4.29	717
9589	300	4	3.14	2	.0105	3.50	800
9588	350	4	3.14	2	.0090	2.71	836
9587	400	4	3.14	2	.0077	2.08	830
9586	500	4	3.14	2	.0063		

Table I

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GEOMETRY OF THE AERIAL VORTEX RING

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Figure 1

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PNEUMATIC VORTEX RING GENERATOR

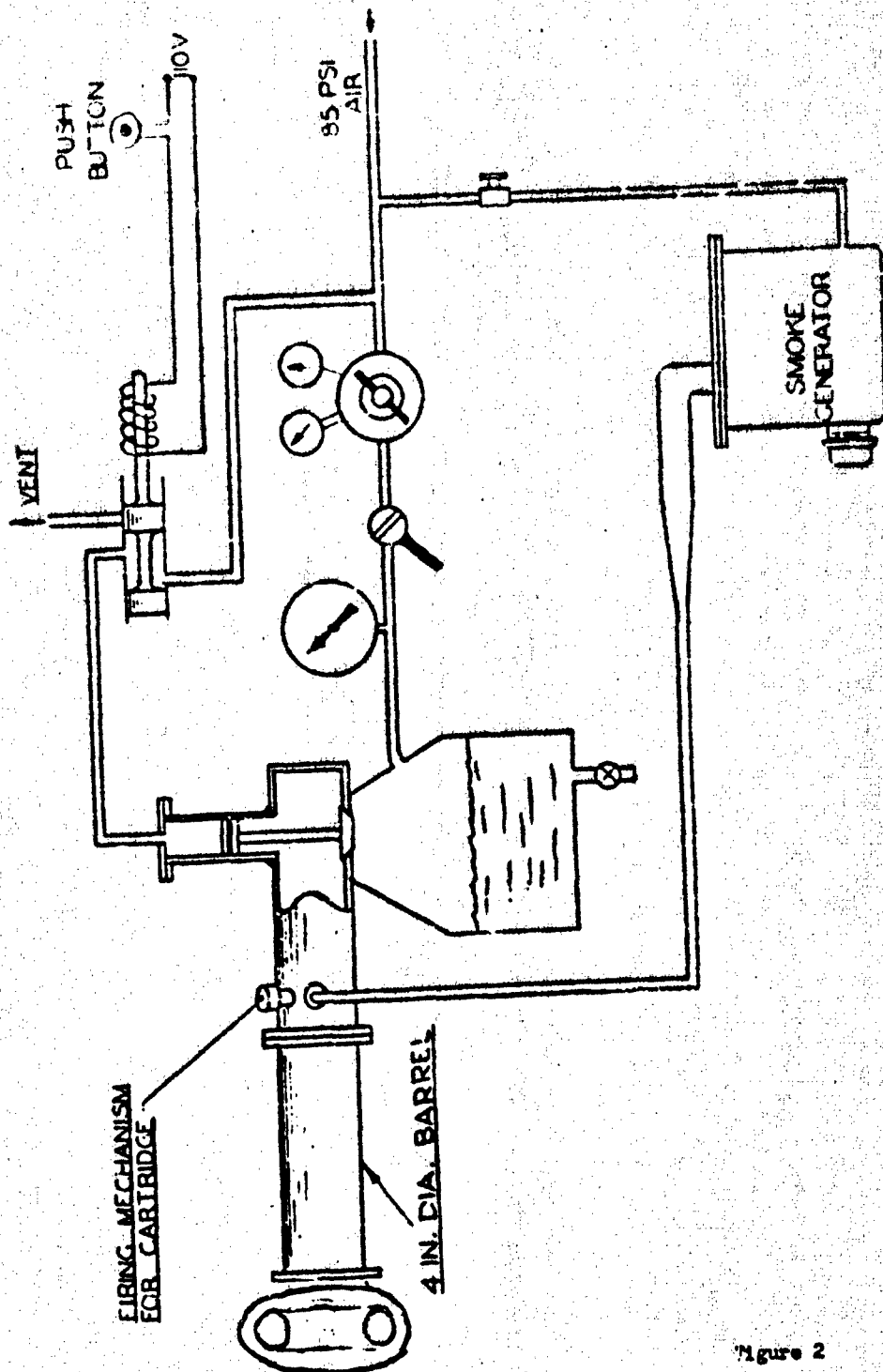
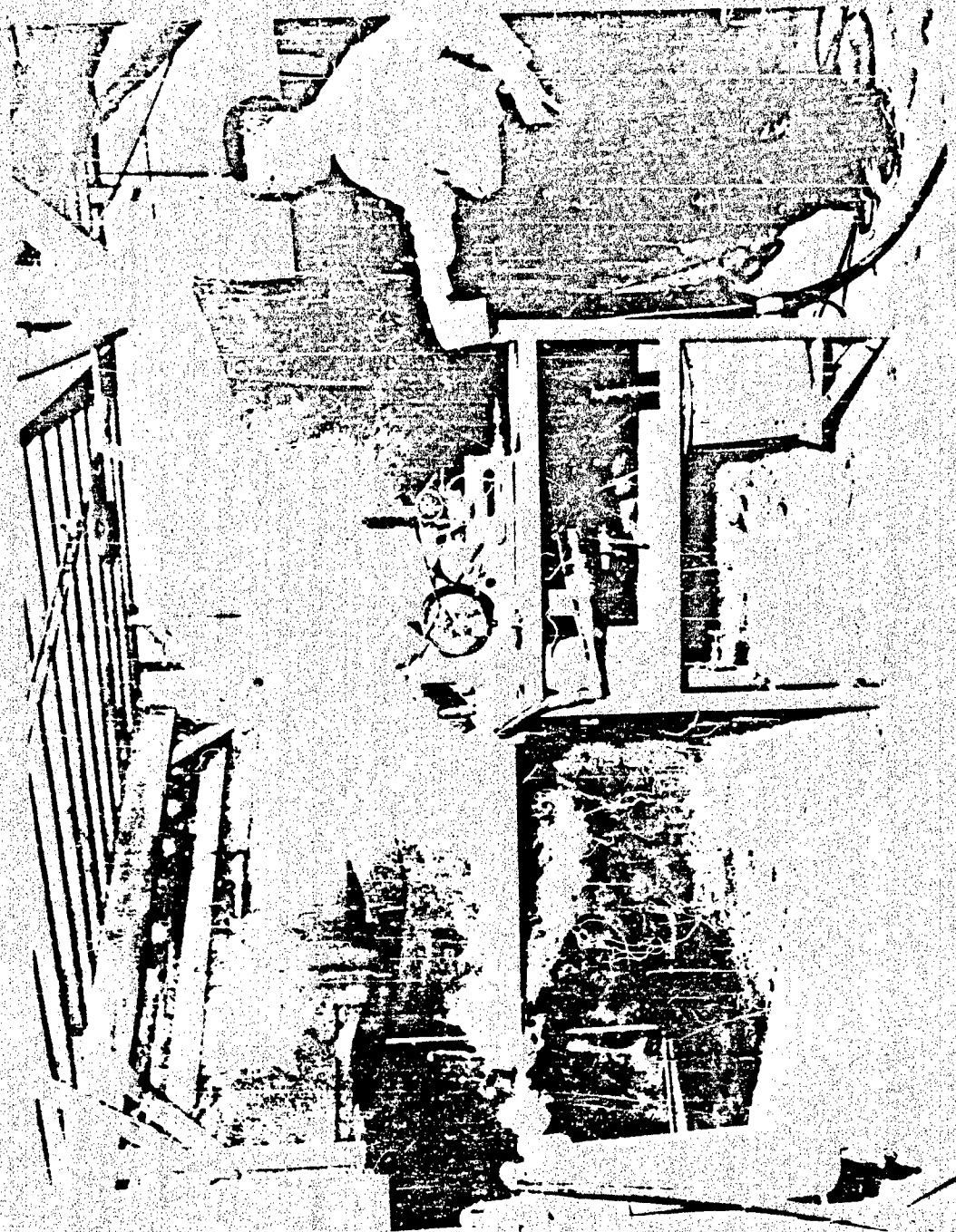


Figure 2

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Pneumatic Vortex-Ring Generator, Photograph

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Figure 3

CONFIDENTIAL

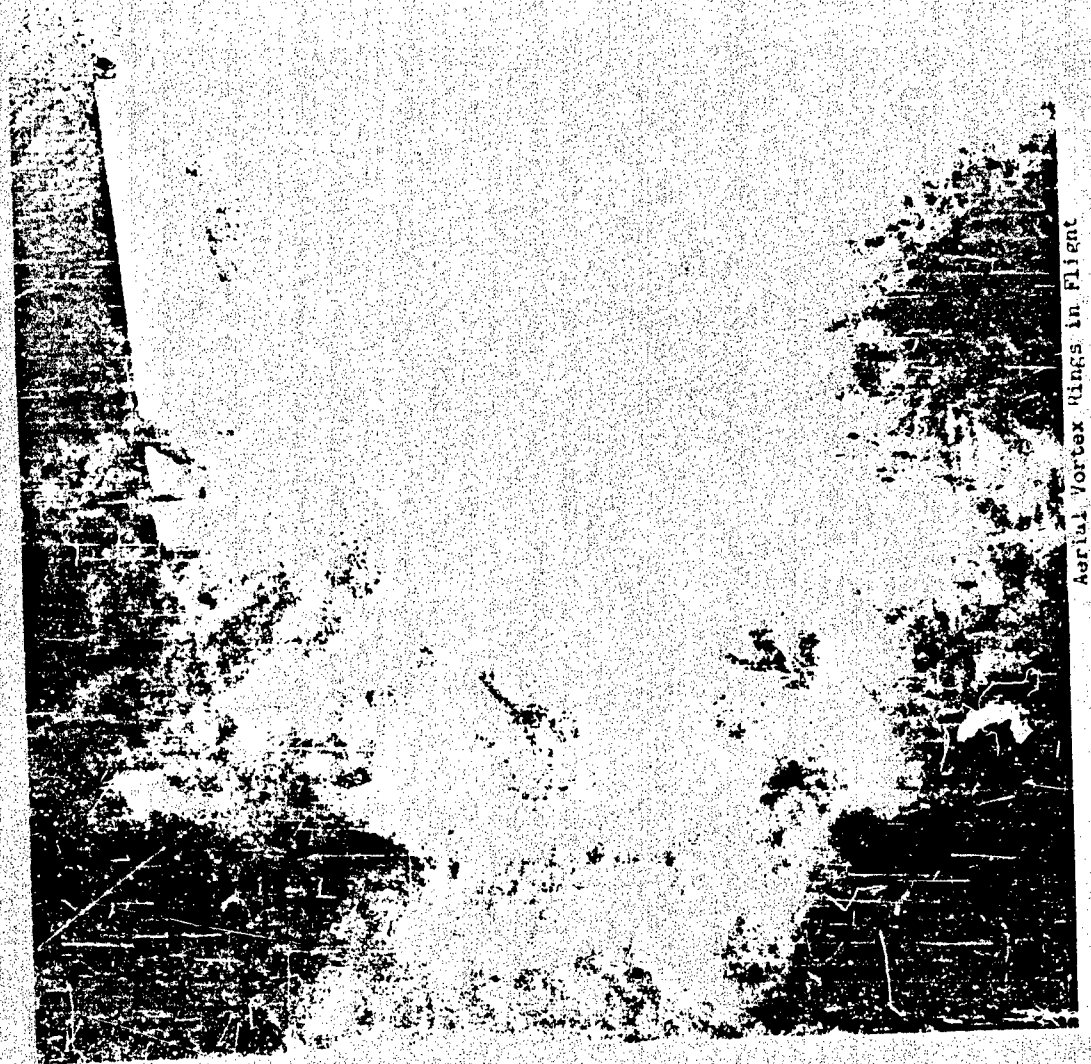


Aerial Vortex Rings in Flight

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Figure 1

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Aerial Vortex Rings in Flight

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aerial cortex rims in film

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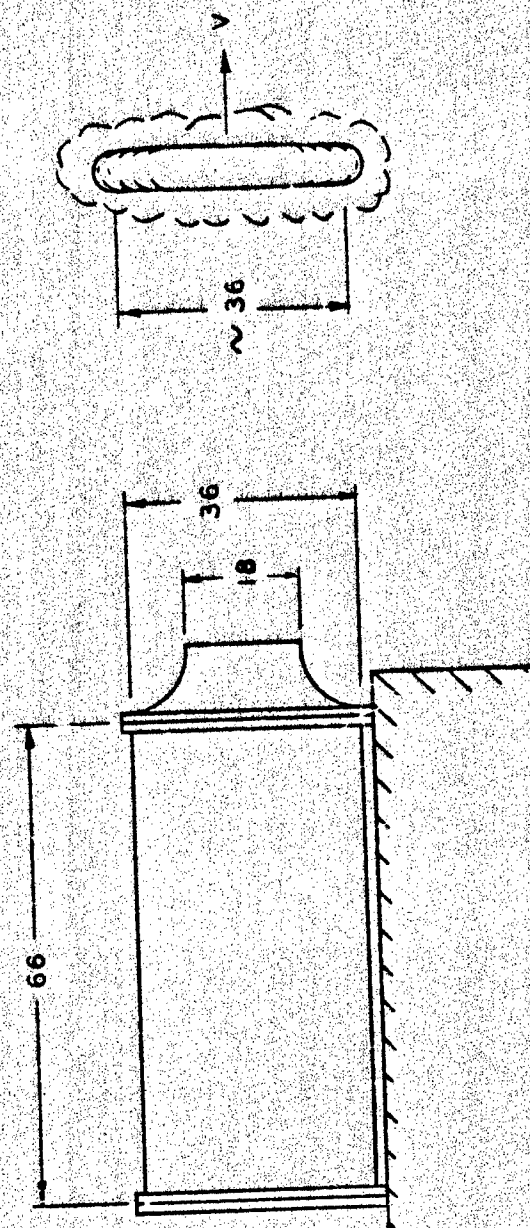


Aerial Vortex Rings in Flight

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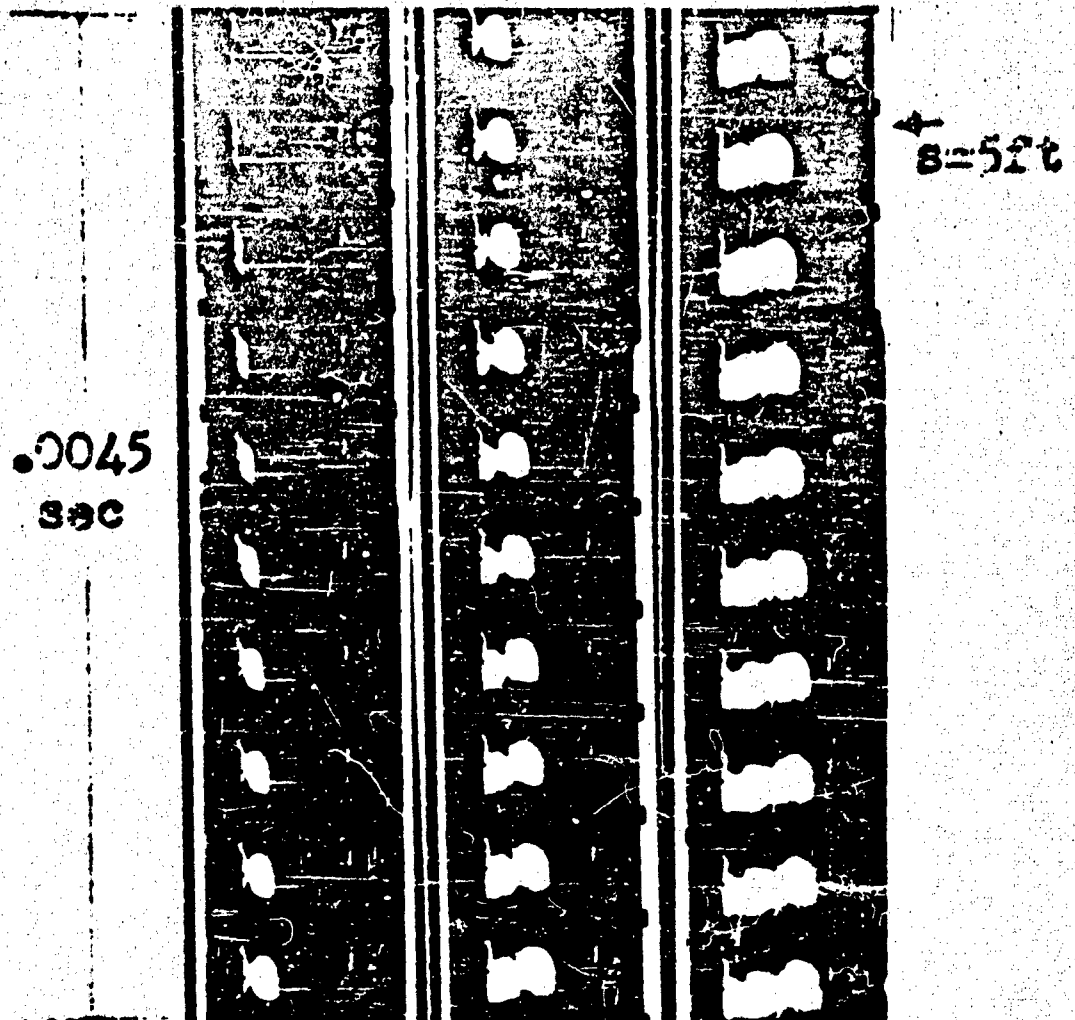
AERIAL VORTEX RING GENERATOR

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Figure 9

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AERIAL VORTEX RING
Charge: 120 gms Black Powder

655-1131

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Figure 10

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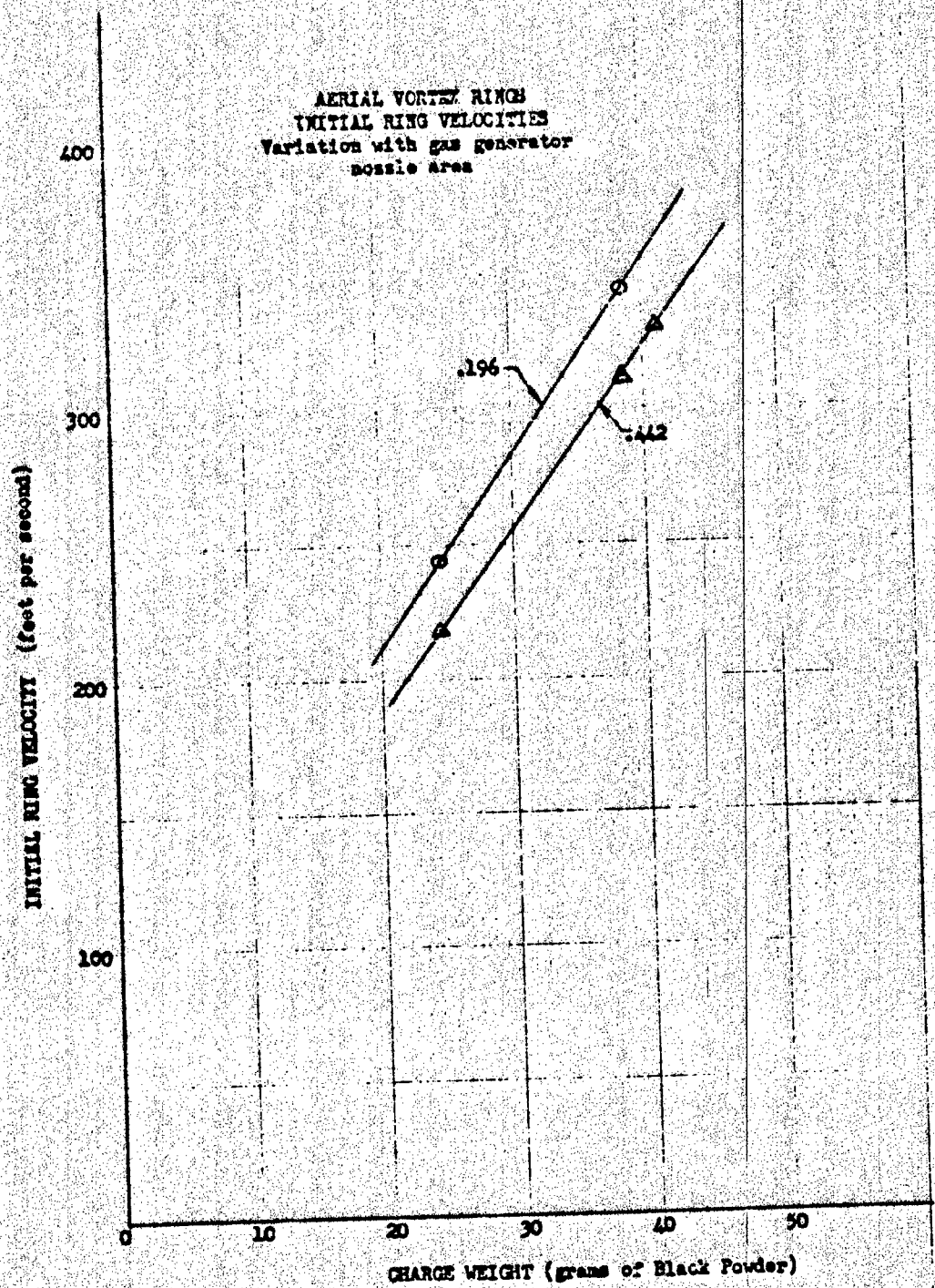


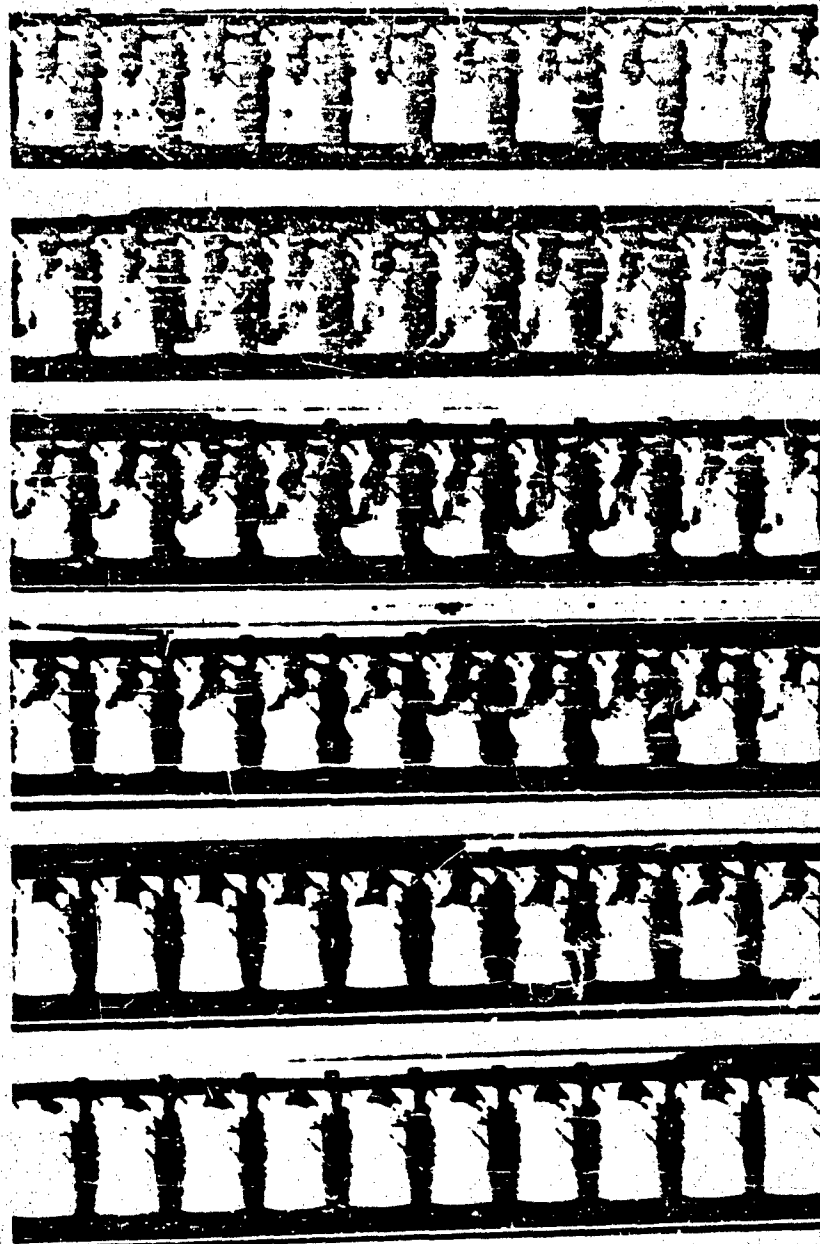
Figure 11

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OFFICE AREA = .25 GENERATOR AREA



AERIAL VORTEX RING

Charge: 38.5 lbs Black Powder

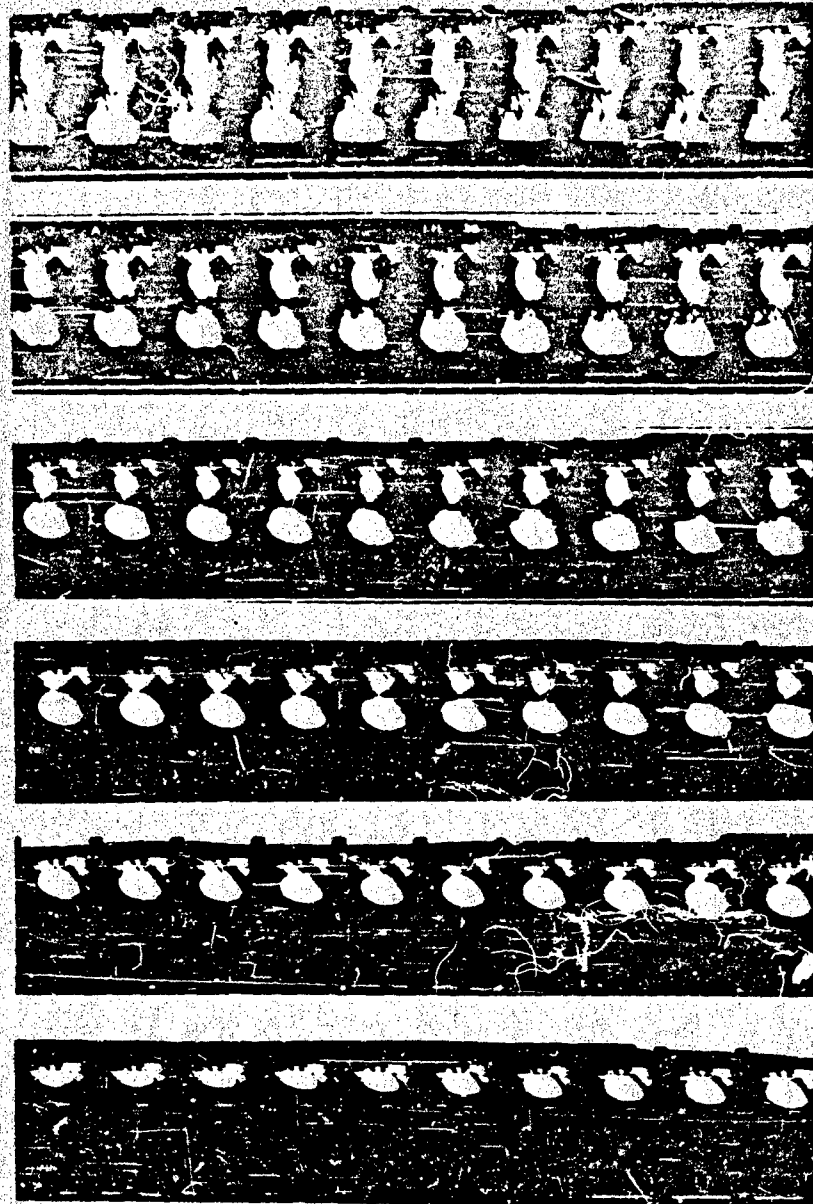
75-3.1

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Figure 12

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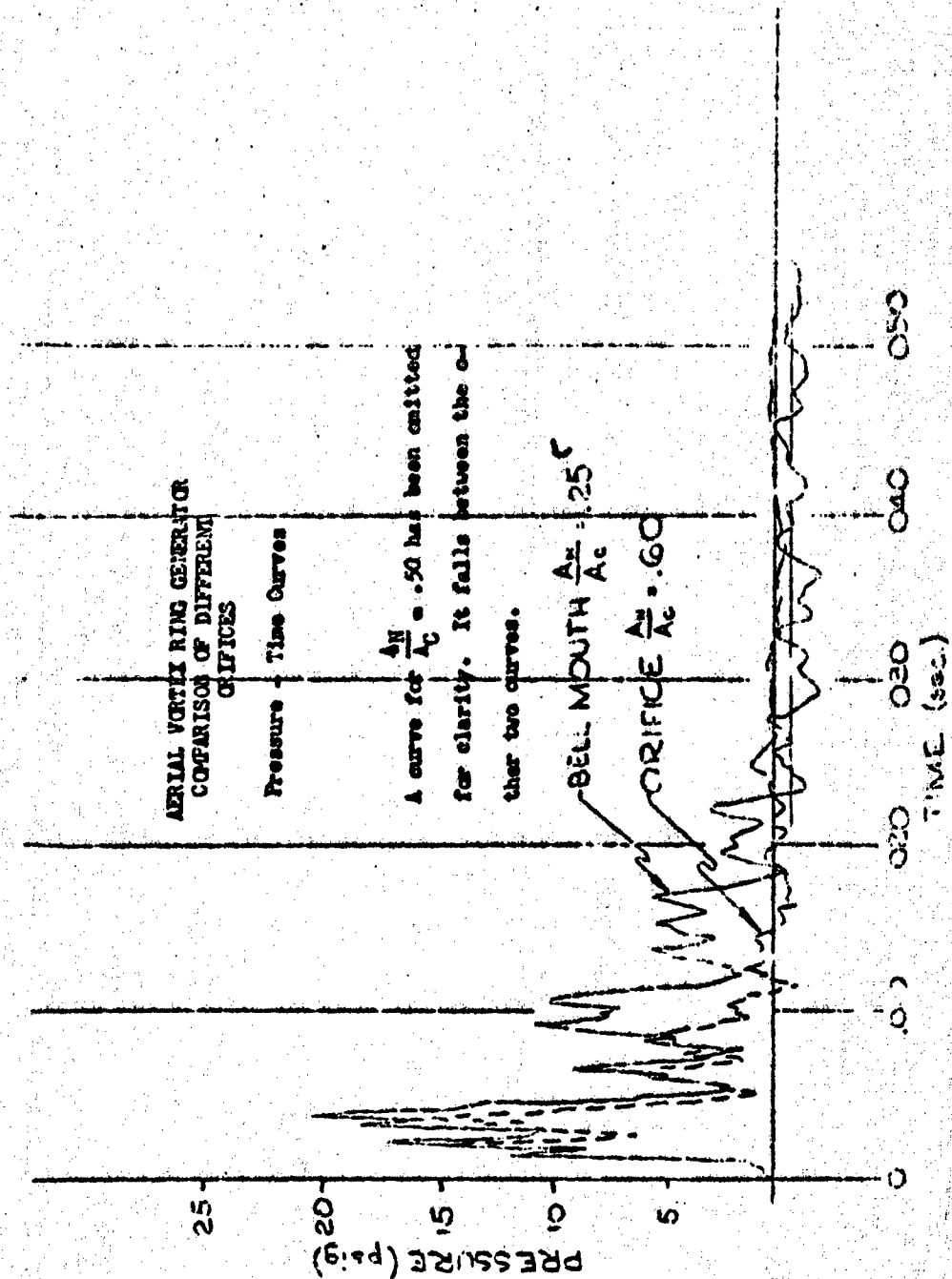
455-002

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Figure 13

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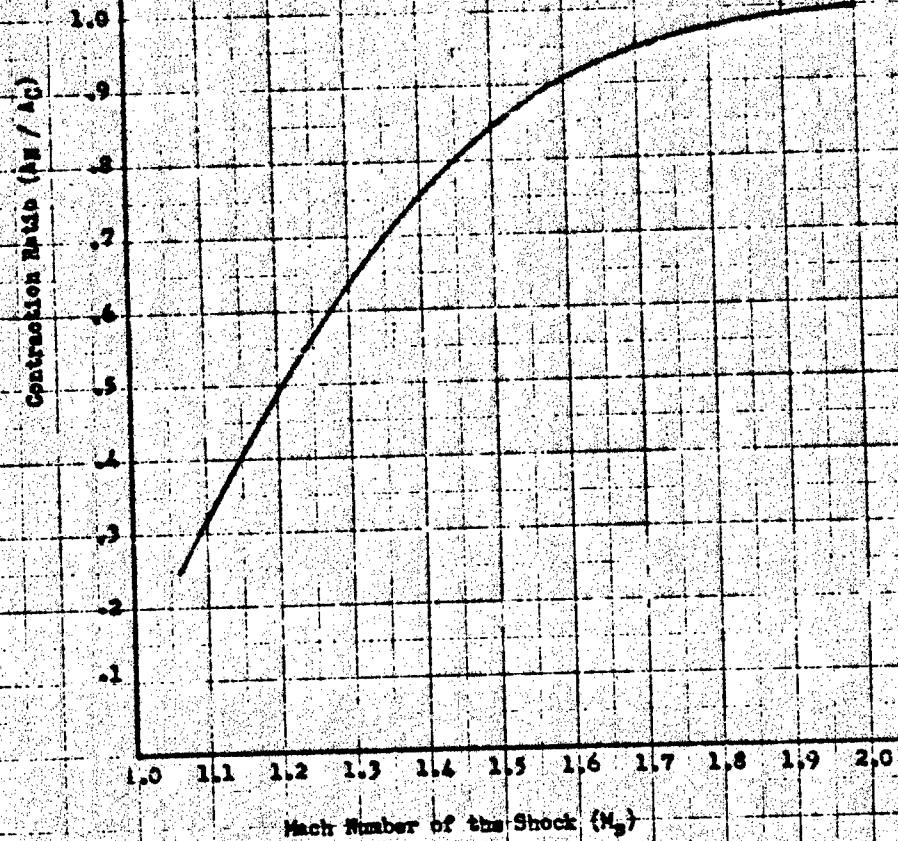
Figure 14

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ACETAL VORTEX RING
CONTRACTION RATIO
For Zero Shock Reflection

Ref: WAVE DIAGRAMS FOR UNSTEADY FLOW IN DUCTS
by G. RÖDINGER (reference 3)



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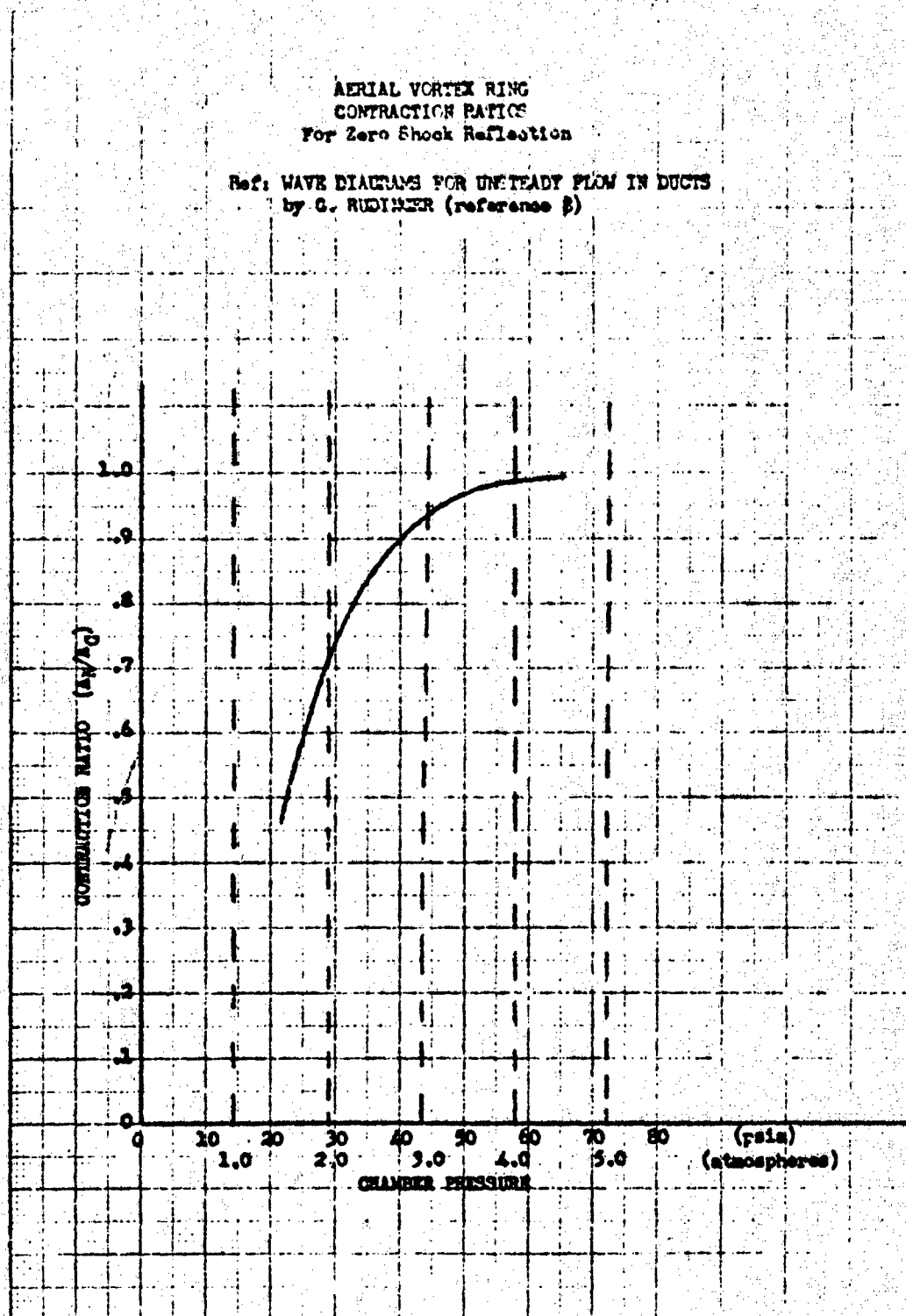
Figure 15

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Report No. 1030

AERIAL VORTEX RING
CONTRACTION RATIOS
For Zero Shock Reflection

Ref: WAVE DIAGRAMS FOR UNSTEADY FLOW IN DUCTS
by G. RUDINGER (reference 3)



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Figure 16

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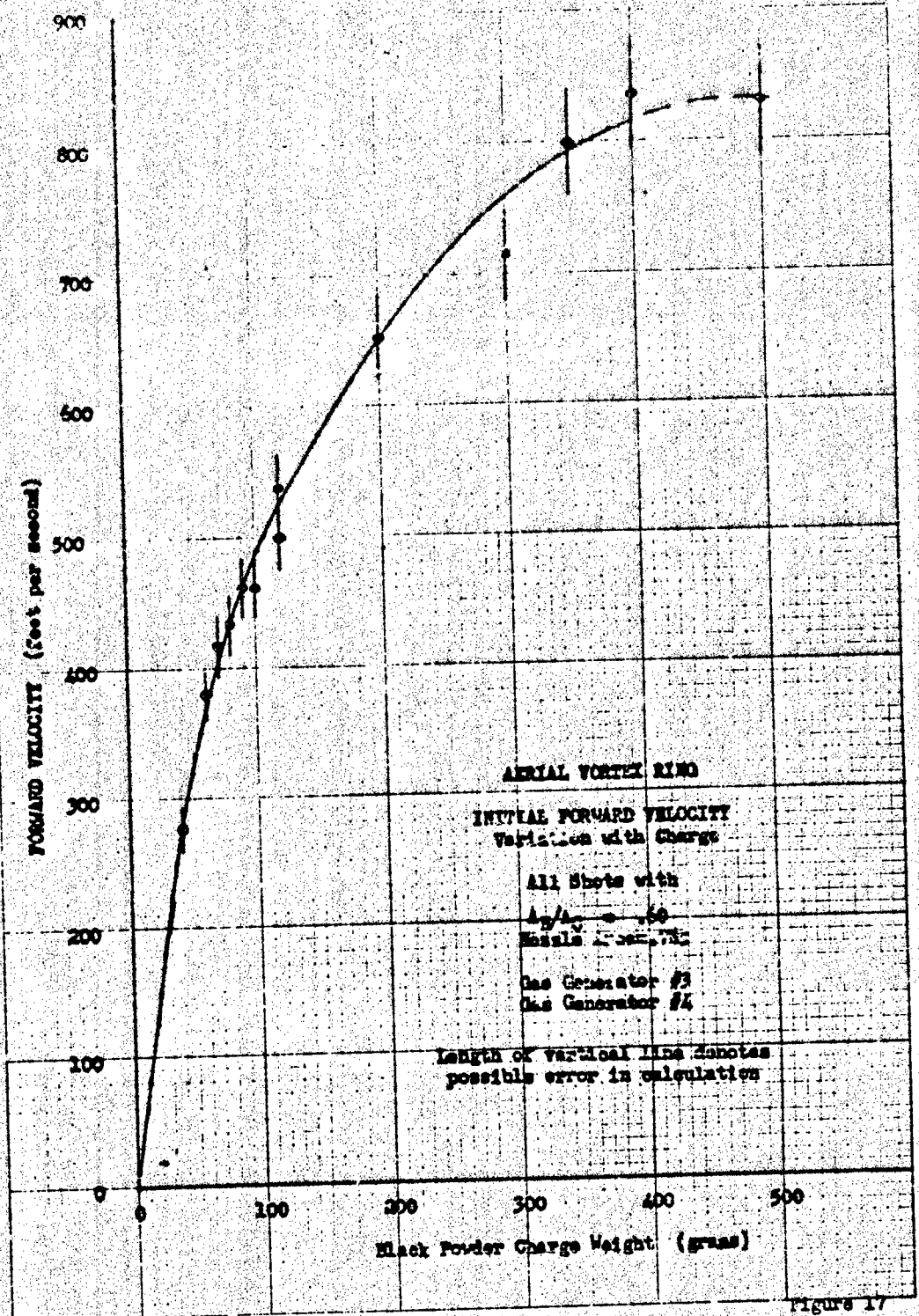
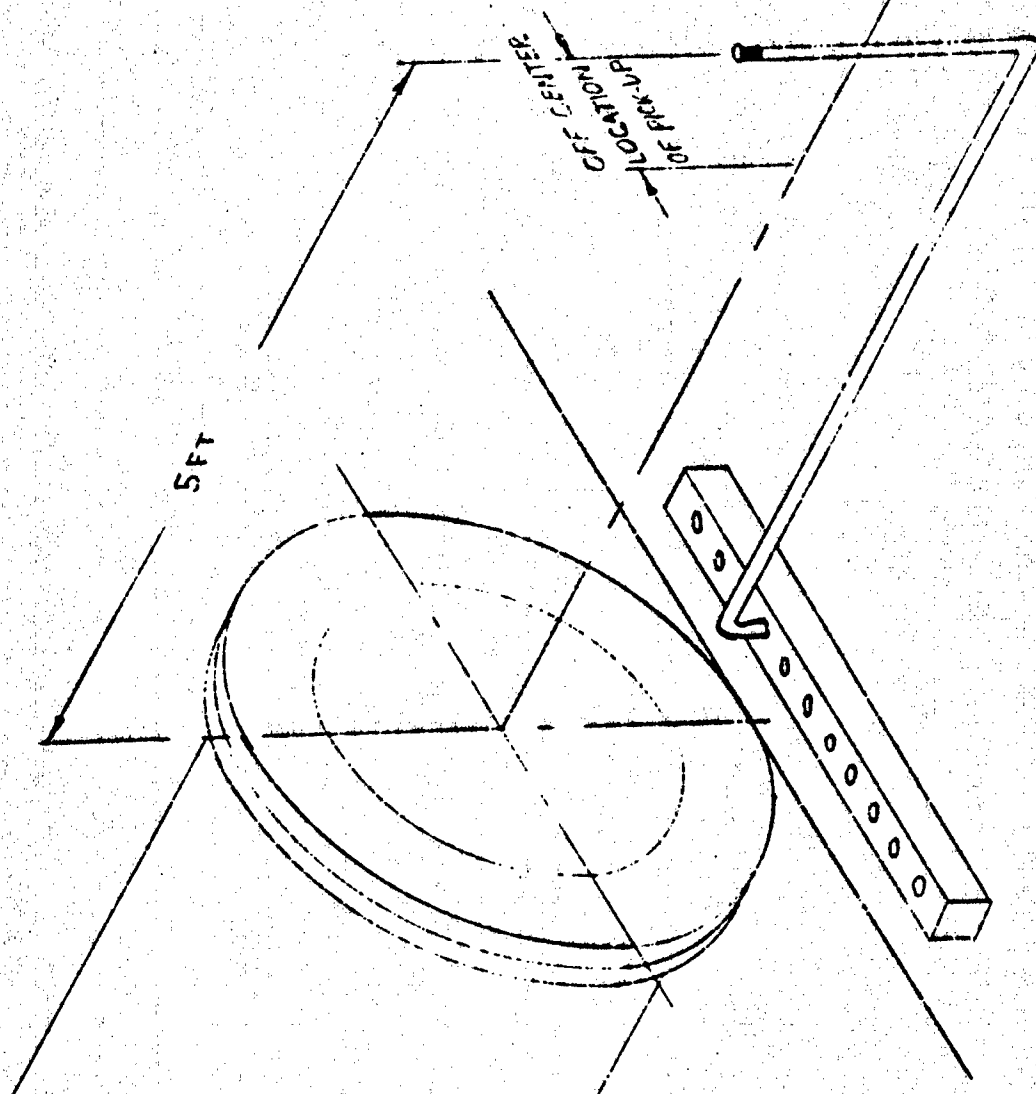


Figure 17

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PRESSURE PICK-UP LOCATED
IN PATH OF VORTEX RING

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Figure 18

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Report No. 1030

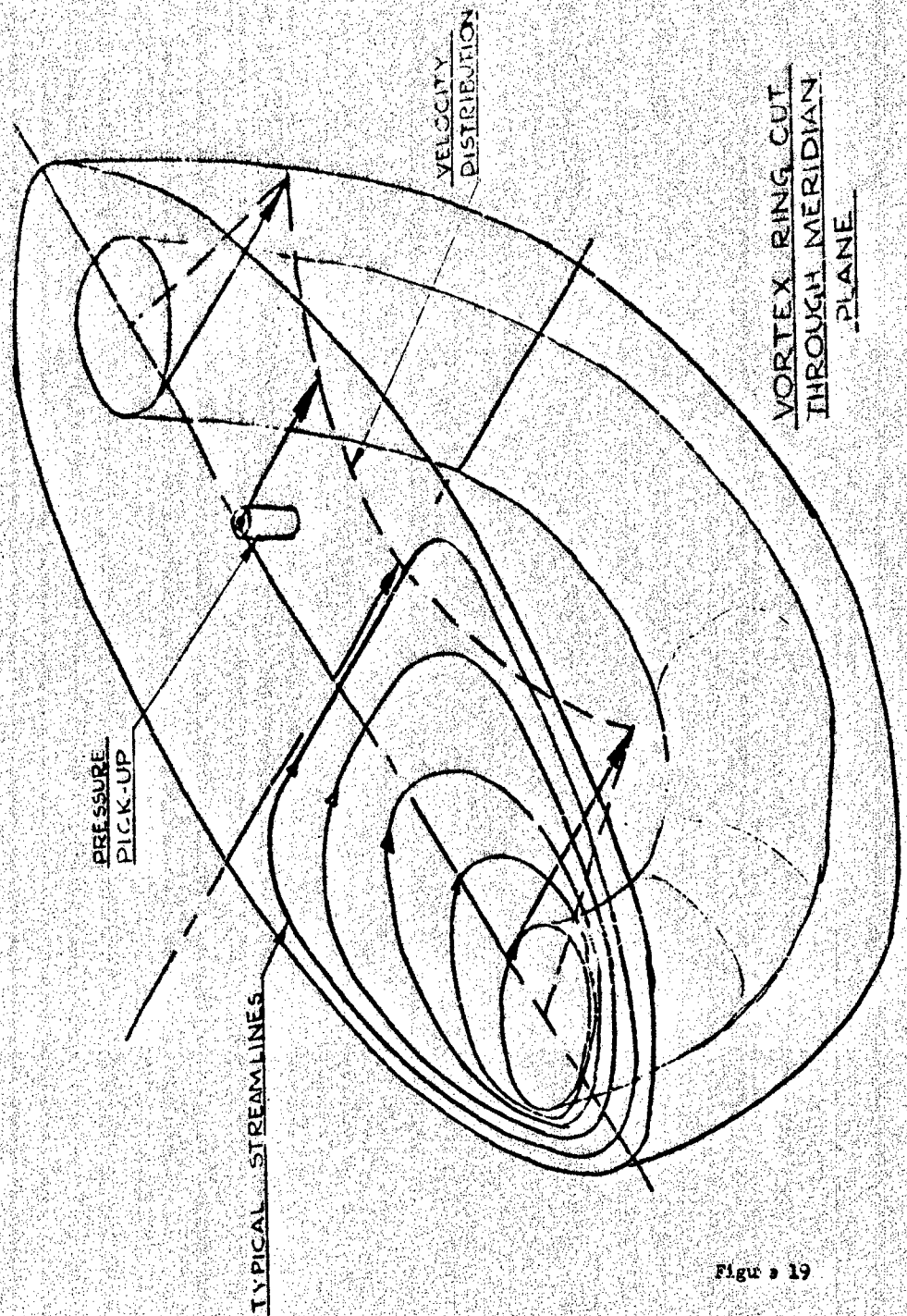


Figure 19

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AERIAL VORTEX RINGS
PRESSURE-TIME DATA

Charge weight-120 gm
14 inches from center line

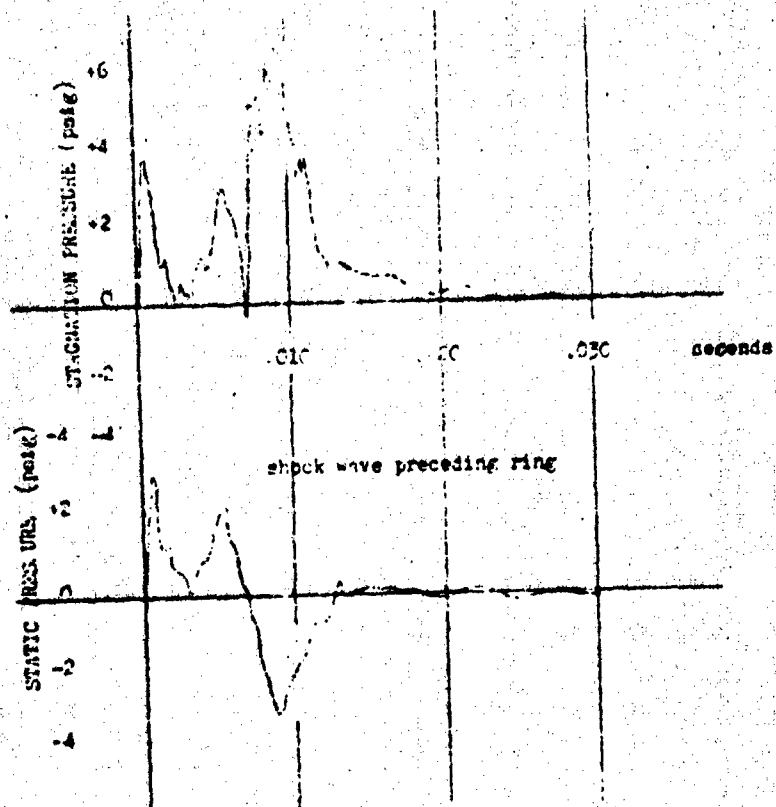


Figure 20

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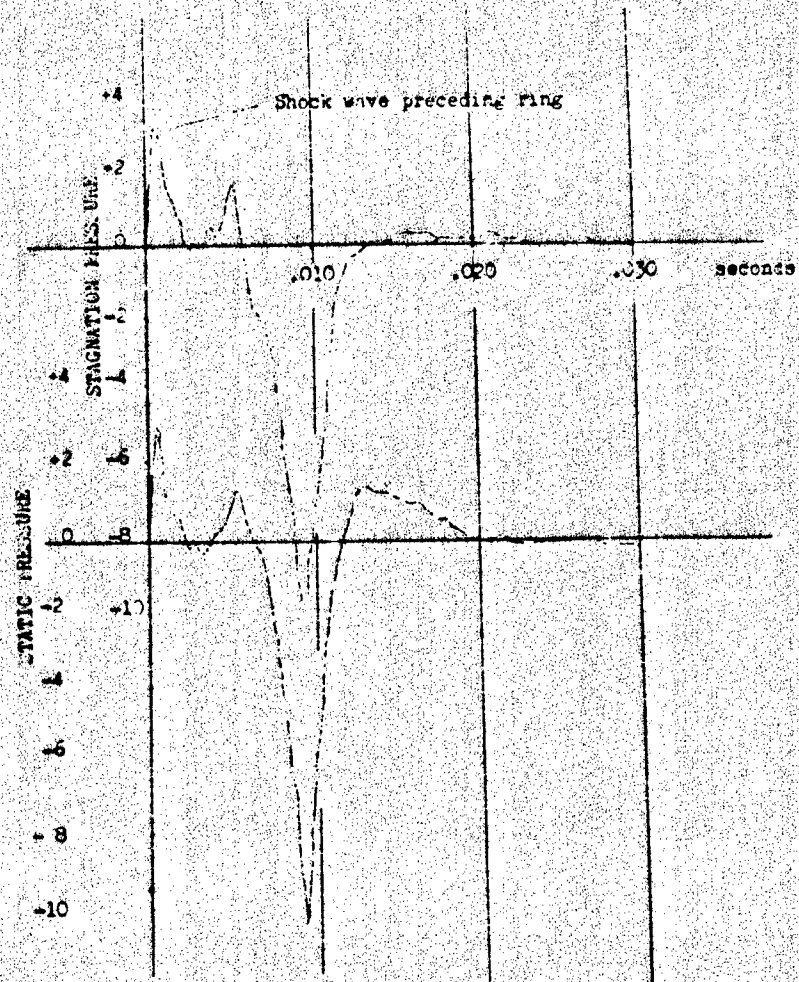
Report No. 1030

AERIAL VORTEX RINGS

Pressure Time Plot

Ring size 1.00 in

2. inches from center line

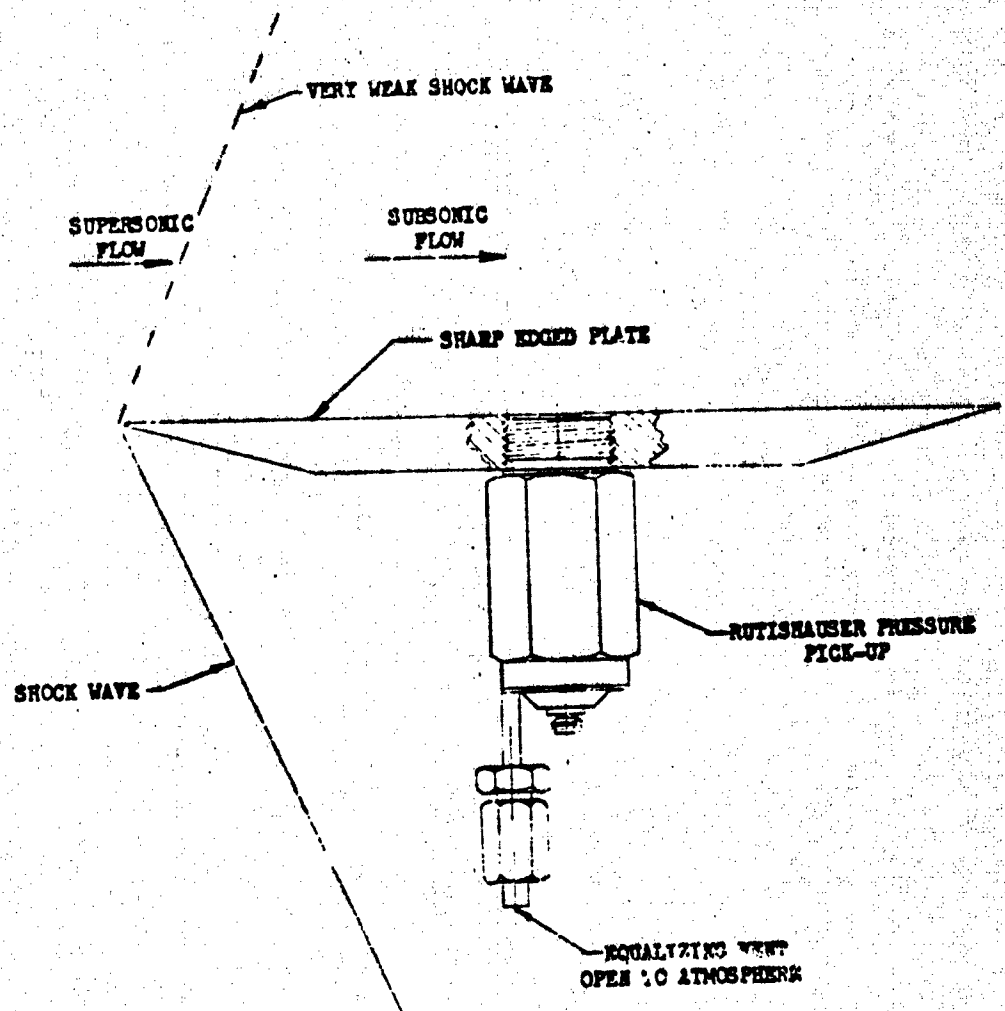


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Figure 21

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SHOCK WAVE IN FRONT OF PRESSURE PICK-UP

SUPERSONIC FLOW

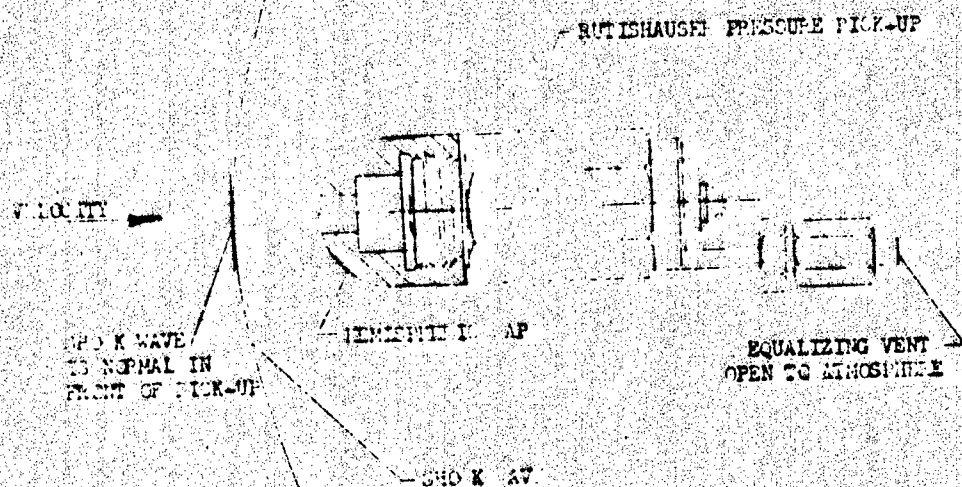
STATIC PRESSURE

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Figure 22

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SHOCK WAVE IN FRONT OF P.T.S. S.E. PICK-UP

SUPERSONIC FLOW

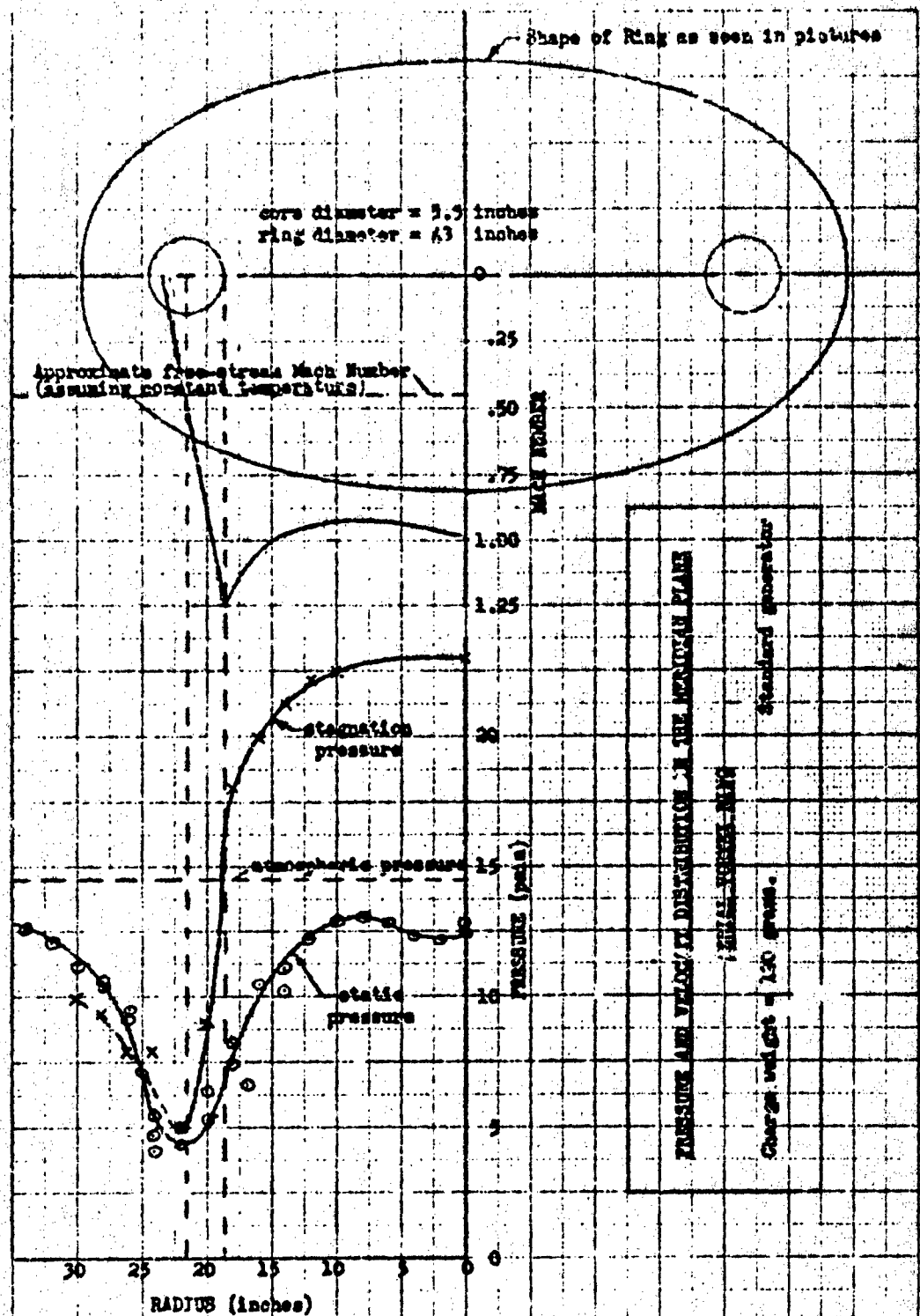
STAGNATION PRESSURE

Figure 23

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Figure 24

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Report No. 1030

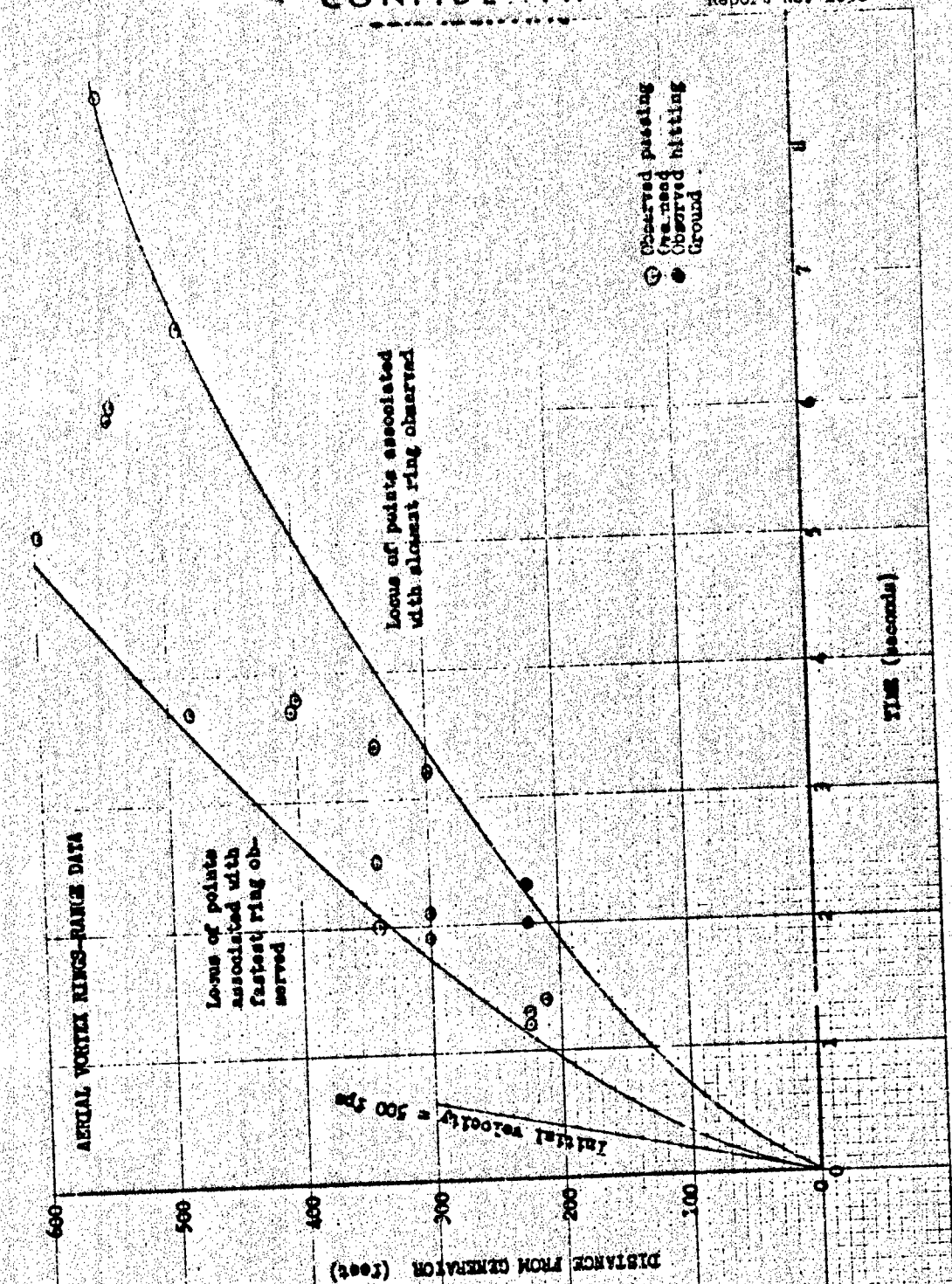


Figure 25

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AERIAL VORTEX RINGS
RANGE DATA

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Replotted from Figure 25

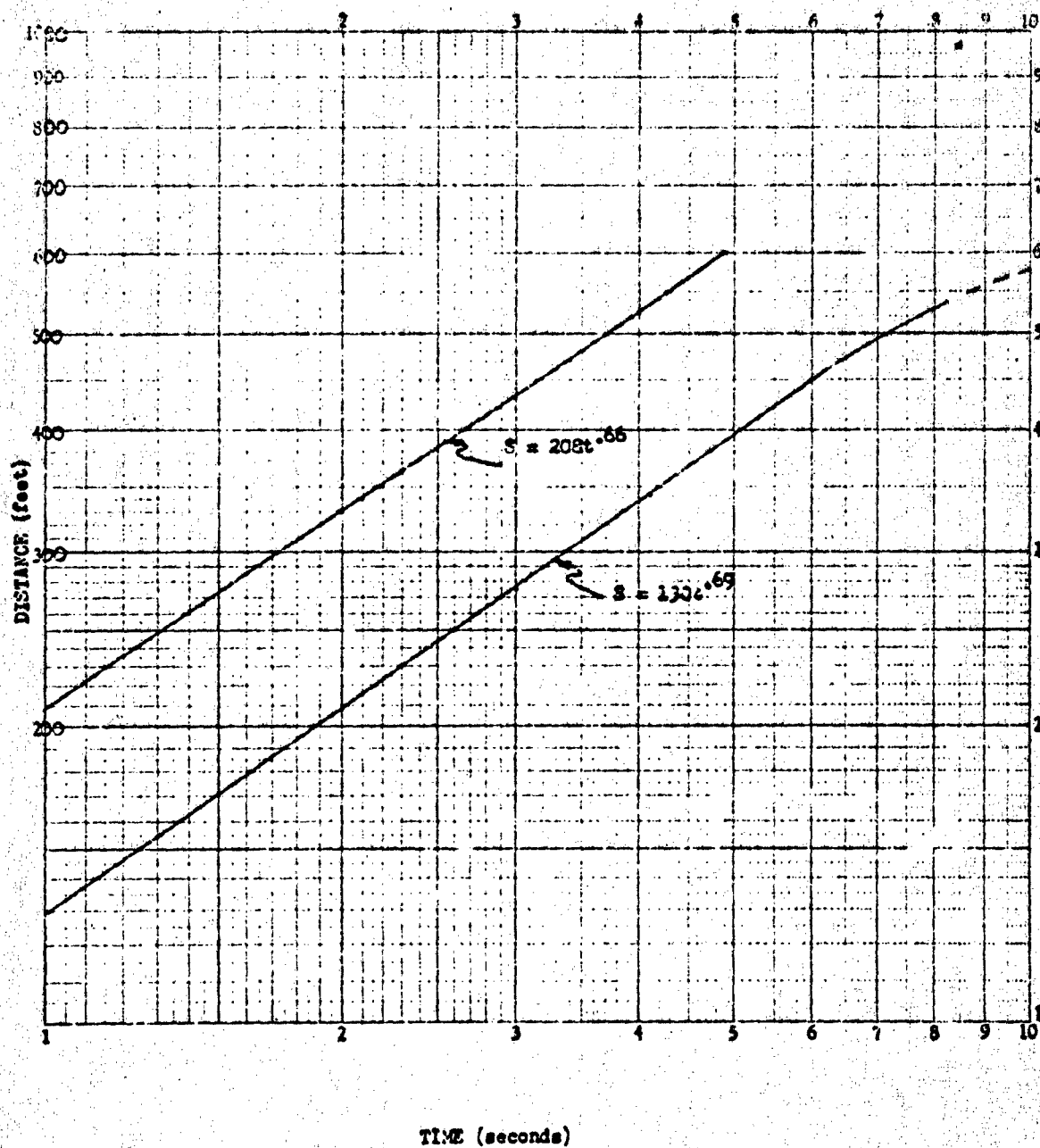


Figure 26

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AERIAL VORTEX RING
TIME-DISTANCE DATA
Charge weight 120 gms

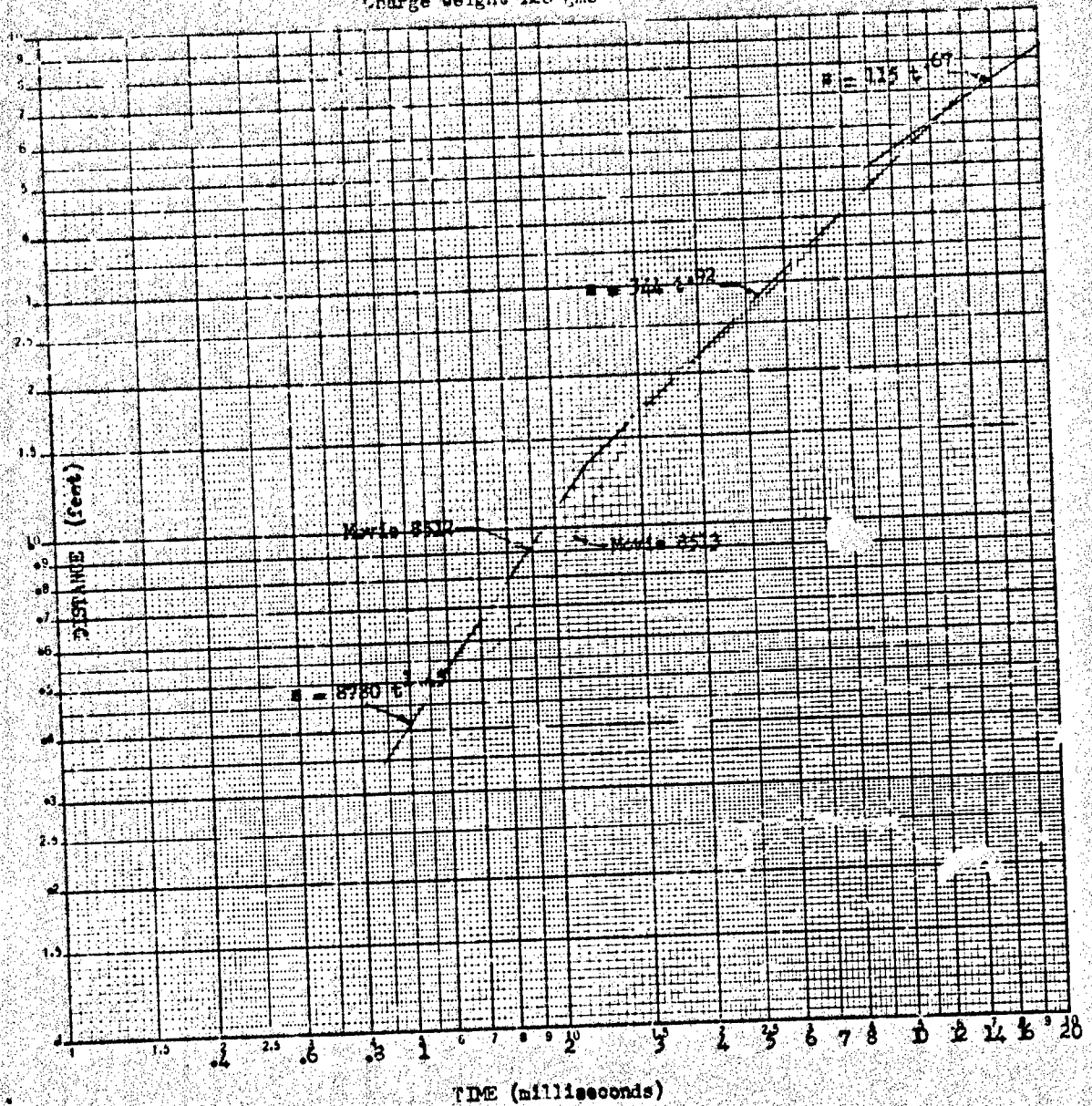


Figure 1.

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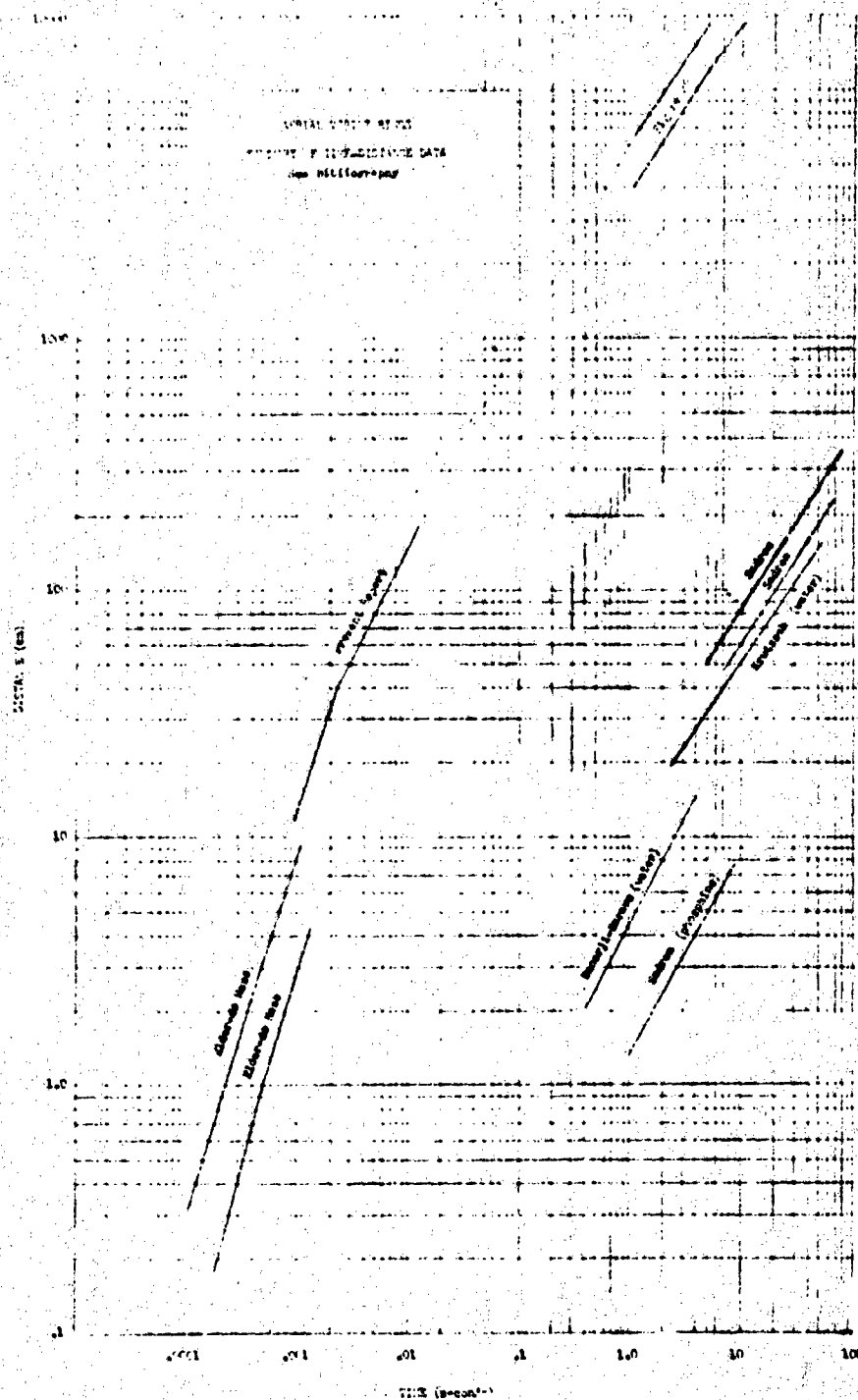


Figure 28

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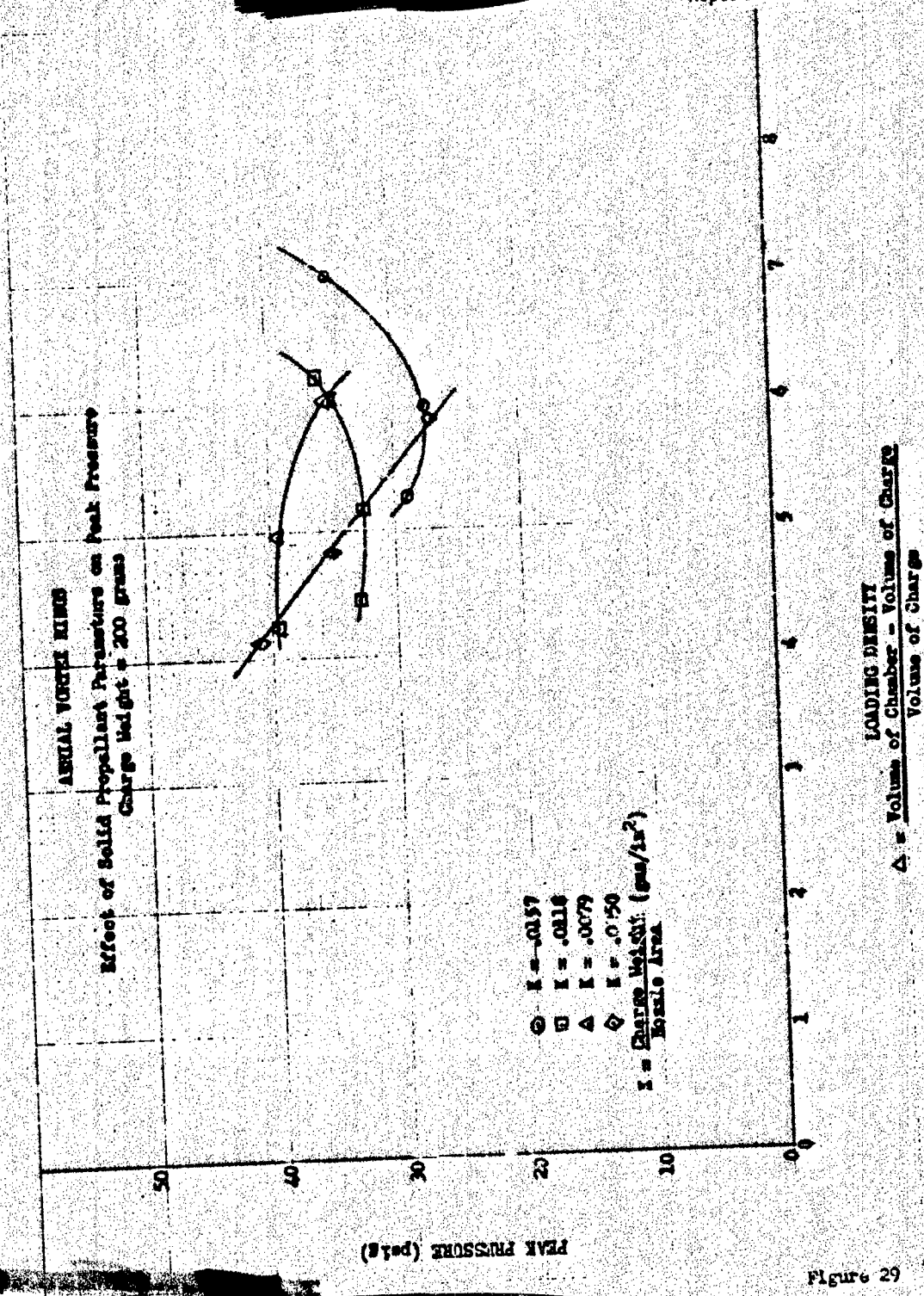


Figure 29

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AERIAL VORTICE
Effect of Solid Propellant Parameters on Peak Pressure
Charge Weight = 200 grams

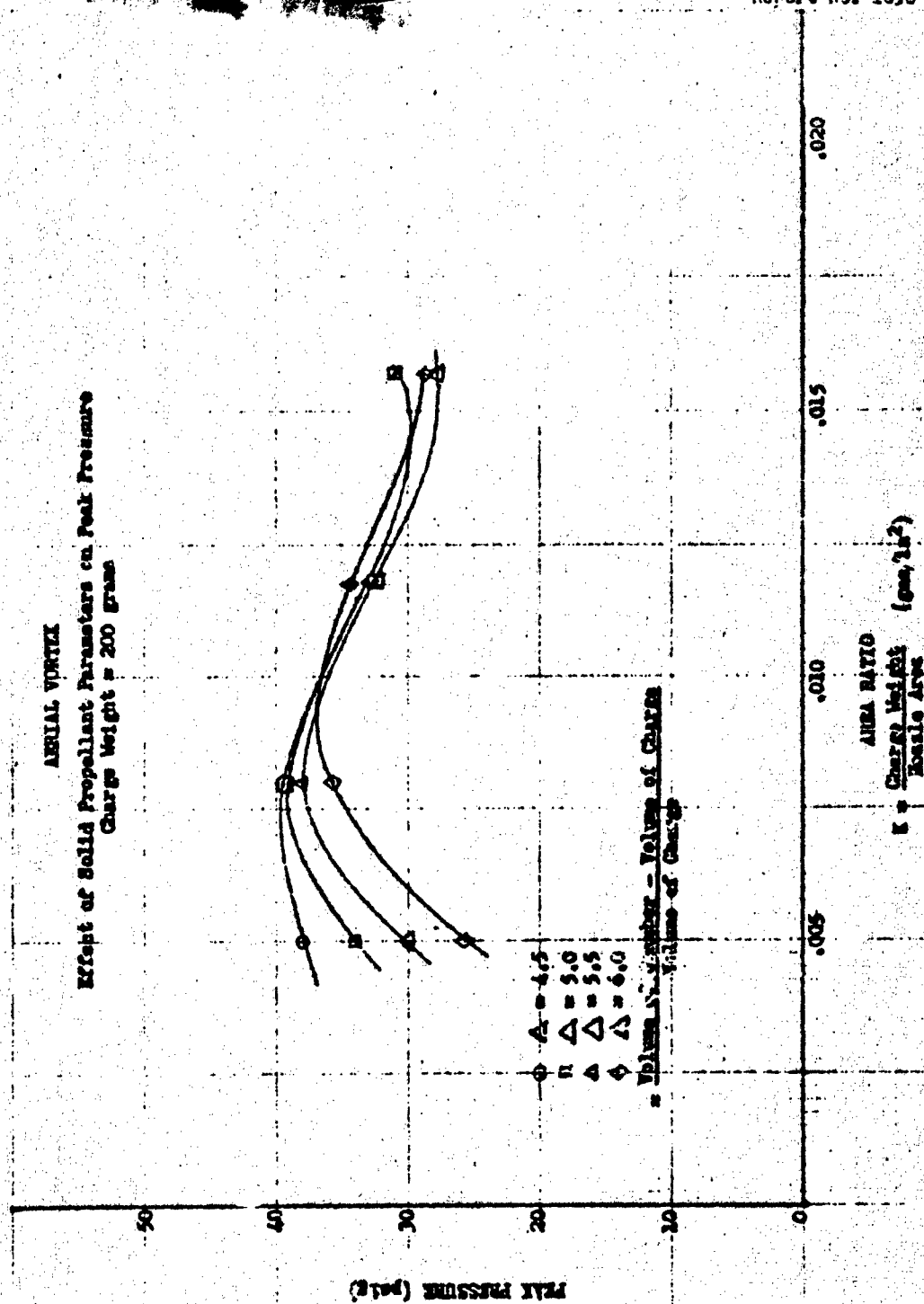


Figure 30

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